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# Firm capacity of PV+STG systems

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**Abstract.** The security of supply becomes a key variable of the electrical system. Due to the discontinuity of solar irradiance, PV generators are essentially not dispatchable and they operate only when there is solar resource but cannot ensure their availability when the energy is needed, so PV systems are considered having a null capacity credit. Energy storage is considered a key for the power sector and its sustainability and different options need to be exploited. The objective of this paper is analyse the optimum size of the required battery, its relations with the peak power of the generation system and the optimum operation setpoint of a PV+STG system for providing firm capacity
.

**Keywords.** Photovoltaics, Storage management, Constant power, Firm capacity.

## 1. Introduction

The implementation of photovoltaic systems is increasingly high in electrical power systems. The electrical generation of PV systems is variable and non-dispatchable, which creates challenges in its integration into power systems. For technical and economic reasons it would be very convenient to provide firmess to photovoltaic generation. Battery energy storage systems (BESS) can offer such firm capacity, giving the system management capabilities for the photovoltaic energy generated.

Certain inherent characteristics of renewable generation make its integration difficult. One of them, perhaps the most important, is the variability of the resource or primary source on which they depend. Due to this dependence on the solar resource, the electricity generation of photovoltaic plants is variable and intermittent and they are essentially not dispatchable. They can only work when there is a solar resource, but they cannot guarantee their availability when energy is needed.

Circulation of large fluctuating currents due to intermittent photovoltaic nature can affect the voltage profiles throughout the network especially in weak networks. Relevant limitations are usually established on the maximum power that can be injected into the network in order to limit these voltage fluctuations.

From an economic point of view, the power generation of PV plants is subject to forecasting errors, incurring in penalizing costs [11]. Besides, with the progressive increase of the installed photovoltaic solar capacity, market prices tend to be very low during the midday hours, causing a "cannibalization effect".

On the other hand, security of supply is a key variable in the electrical system. Firm energy determines the maximum volume of energy that a generation unit can sold at a given reliability level. Capacity value (or "capacity credit") indicates the extent to which VRE can be relied upon like conventional power plants. The capacity value of photovoltaic (PV) solar is very low[1] - [2] - [3]

There are many advantages that Battery energy storage systems (BESS) offers to photovoltaic systems, being a key element linked to the development and penetration of photovoltaic solar energy that is expected over the next few years. The installation of batteries in parallel allows to reduce overgeneration and curtailment and the sale of energy in the hours of greatest production. Battery energy storage systems (BESS) can offer firm capacity, providing the system with management capabilities for the photovoltaic energy generated.

For all the above, the concept of constant photovoltaic power generation (PV-CPG) arises to overcome these problems. Problems of voltage variations due to variable currents, ramps, the need for backup sources cannibalization effect etc. are reduced.

## 2. Objectives, methodology and some results

The objective of this work is to study the most appropriate relationship between the capacity of the storage system and the peak power of the photovoltaic generator that allows the delivery of a firm power throughout the year. Analysis parameters are presented that allow deciding the most convenient constant power value (PV-CPG setpoint) and the size of the storage system, as well as studying management strategies to reduce its deviation with respect to the predefined PV-CPG setpoint. These parameters are the energy deficit, the energy surplus, the energy deviation and the equivalent number of cycles of the battery.

The proposed ES management strategy is derived from a methodology that considers the interaction with the grid for different sizing factors and battery sizes, and different scenarios such as annual or monthly constant power.

As a case study, the evolution of the parameters in a 1MWp photovoltaic system located in Zaragoza, (Spain) with battery is analyzed.

Figure 1 shows the hourly production of the photovoltaic installation (EPV, h) and in blue the energy injection that was attempted to be achieved for one day. It can be seen that in a photovoltaic installation the hourly generation is highly variable, with moments of high generation, and others of zero production.

The ESS is aimed at correcting the differences between the generated (EPV,h) and the constant energy setpoint (ECPS,h), in order to provide a PV firm power. Within the central hours of the day, as EPV,h is greater than ECPS,h, the ESS is intended to absorb the corresponding surplus of energy. However, when EPV,h is lower than ECPS,h, the ESS is intended to deliver the energy needed to maintain the constant power setpoint.

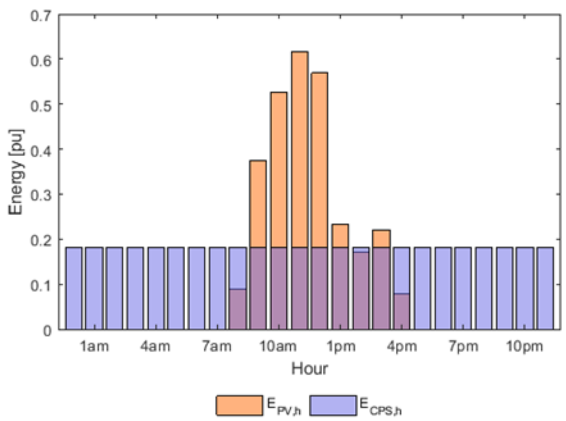



Figure 1. Constant energy setpoint (ECPS,h) and energy produced by the photovoltaic installation (EPV,h) within 1 day.

Figure 2 shows a typical duration curve over 11 years of a 1 MWp photovoltaic installation, without storage. The generation duration curve (GDC) is a curve commonly used in generation systems in which the hourly generation values are presented in descending order. You can quickly see the number of hours (or as a percentage of the total time) in which the generation exceeds a certain value. The variability of generation is evident as well as the fact that the distribution infrastructure, which must be designed to withstand generation peaks without risk, is underused much of the time.

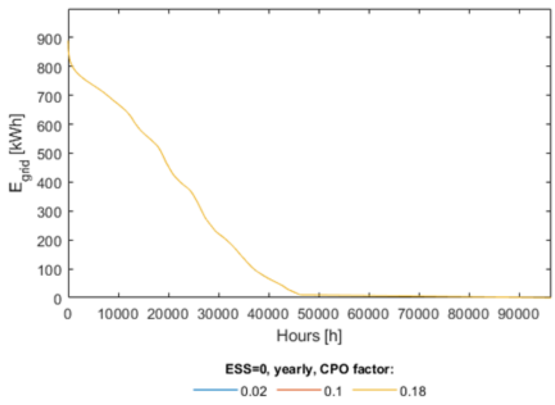



Figure 2. Generation duration curve without storage.

With a system that provides constant power, the duration curve would ideally be a horizontal line, the installation being able to provide firm power, of the established value (constant power setpoint).

Another very useful parameter in the analysis of production in an electricity generation plant is the capacity factor. The capacity factor of an electricity production plant is a dimensionless parameter that is defined as the quotient between the energy produced annually and the power product of the installation times the number of hours in a year (3). The product of power and number of hours can be interpreted as the production of the plant if it were generating all the time at maximum power. Therefore, in the case of a photovoltaic plant, its capacity factor CFPV is an indicator of the percentage of energy produced with respect to its maximum capacity. From the point of view of a constant power installation, it would be the maximum generation value that could be maintained during all hours of the year.

However, it must be noted that if the relative sizes among the Wp of the PV installation (PPPV), the ESS capacity ($C_{ESS}$) and the constant energy setpoint ($E_{CPS,h}$) are not adequately set, there may be deviations of the actual energy supplied to the grid ($E_{GRID,h}$) with respect to $E_{CPS,h<}$.

The desired $E_{CPS,h}$ value may not be reached at certain times of the year, (therefore there is an energy deficit in that hour), and in others the amount that exceeds cannot be stored due to the already full battery, a situation that we will consider as a surplus with respect to the established constant power.

The constant power operation factor ($CPO_{factor}$) is defined here as the constant power setpoint to be supplied to the grid $P_{CPS,h}$ divided by the peak power of the photovoltaic installation ($P_p$). Since the calculations are hourly-based, the $P_{CPS,h}$_value coincides with the previously $E_{CPS,h}$ value.

The Storage to Power ratio (S2P) represents the relative size between the ESS capacity ($C_{ESS}$) and the peak power of the photovoltaic installation (Pp),

S2P $=C_{ESS}/Pp$

S2P has dimension of time in hours [Wh/W, hours]. The factor $C_{ESS}/P_{CPS}$ accounts for the relative size of the ESS and constant power setpoint and represents the amount of hours that the $P_{CPS}$ could be delivered if we start from the fully charged battery, that is, it is something like the hours of autonomy in isolated installations.

On the other hand, the factor $P_{CPS}/P_P$ represents the relative size of constant power setpoint and the peak power of the photovoltaic plant (CPO factor). In this way CPO and S2P can be easily related.

Given a PPV we are interested in looking for the most appropriate value of storage capacity that allows us to work with a target factor CPO, or the optimal CPO value that we could propose in the operation of a plant with a given peak power ($P_P$)and ES capacity ($C_{ESS}$).

Analysis parameters

To quantify the hourly energy deviations from the constant power setpoint, the following parameters are used. For this purpose, hT represents the total number of hours covered in the analysis.

The energy deficit (ED) is defined as the energy that the system cannot supply ($\sum E_{DEF,h}$), divided by the annual energy must be supplied ($\sum E_{CPS,h}$), throughout the considered hT period. This percentage represents the negative energy deviation with respect to constant power setpoint, due to negative differences between power generation ($E_{PV,h}$) and the constant power ($E_{CPS,h}$),

The energy surplus (ES) is defined as the energy that the ESS cannot store ($\sum E_{SUR,h}$), divided by the hourly energy that must be supplied ($\sum E_{CPS,h}$), throughout the considered hT period. This percentage represents the positive energy deviation with respect to the constant power setpoint, due to positive differences between power generation ($E_{PV,h}$) and the constant power ($E_{CPS,h.}$)

The number of non-compliance hours is a complementary measure associated with the previously defined ED, ES and TED indices and such index reflects the total number of energy deficit, surplus or net deviation hours throughout hT. The mentioned number of equivalent hours represent a fine adjustment to quantify for a given CPO factor and from a specific ESS size on, the number of hours within a year for which the firm PV plant does not reach the CPO factor. Depending on the impact that such mismatch would cause on the nearby electrical grid, they would also account for the number of hours for which the PV plant holder would receive a penalty, and therefore they can be viewed as non-compliance hours.

The number of equivalent cycles of ESS. The aging of the ESS depends on the number of full charge cycles and the temperature value, among others. Generally, full charge cycles are not performed due to conditions imposed to meet constant power supply. Nevertheless, the ESS has a limited number of charge cycles, so a measure that accounts for this quantification is necessary in order to estimate the ESS degradation. Therefore, a way to quantify the charge cycles of the ESS consists in dividing the input energy of the batteries ($E_{BAT,\ h}$) summed throughout a hT period by the ESS capacity ($C_{EES}$). The resulting parameter is called the number of equivalent cycles (NEC). This value is equivalent to the number of charge and discharge cycles that the manufacturer provides to quantify the useful life of the battery.

The ESS operating conditions for each hour are modelled through an algorithm that is shown in Figure 3. The initial condition of the batteries is a SOC of 50%.

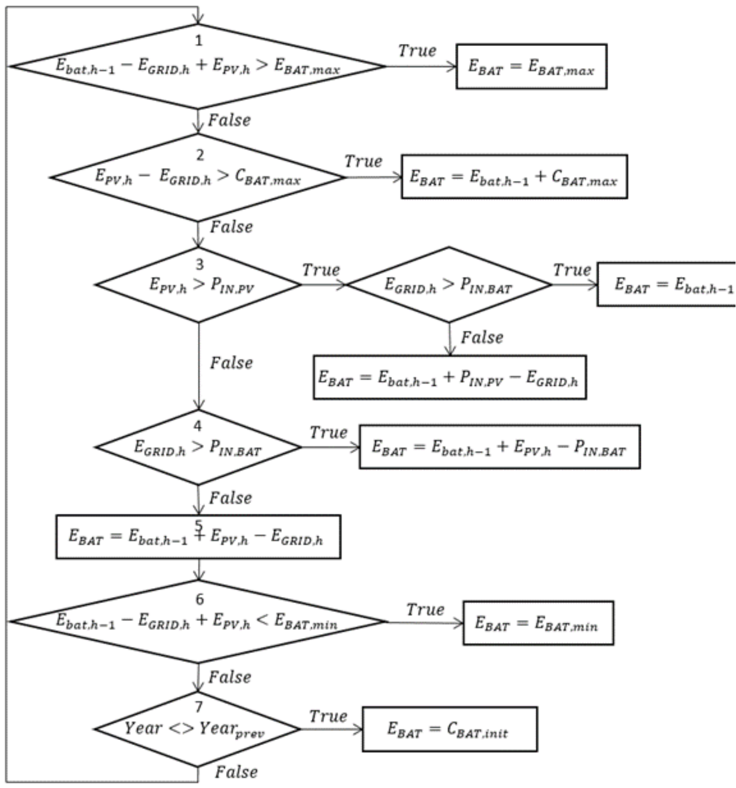



Figure 3. Algorithm for the management of PV-ESS system.

The algorithm in Fig. 3 is composed by several stages that are hereafter detailed, where, for the sake of simplicity, only the true answers are described:

- If the SOC in the previous hour (h-1), summed to the energy balance ($-E_{GRID,h}+E_{PV,h}$) in the current hour (h) exceeds the maximum storage capacity ($E_{BAT,max}$), then the ESS current capacity ($E_{BAT}$) is limited by its maximum capacity ($E_{BAT,max}$).
- If the instantaneous power of the energy balance ($E_{GRID,h}+E_{PV,h}$) exceeds the maximum power of the EES ($P_{BAT,max}$), then the SOC of the battery is updated to the SOC in the current hour (h-1) and the maximum power of the EES ($P_{BAT,max}$).
- If the instantaneous power of the energy balance ($-E_{GRID,h}+E_{PV,h}$) exceeds the maximum power of the EES ($P_{BAT,max}$), then the SOC of the battery is updated to the SOC in the current hour (h-1) and the maximum power of the EES ($P_{BAT,max}$).
- If the photovoltaic energy produced ($E_{PV,h}$) exceeds the PV inverter power ($P_{IN,PV}$) the photovoltaic energy generated is limited. If the energy supplied by the PV-ESS system ($E_{GRID.h}$) exceeds the ESS inverter power ($P_{IN,BAT}$) then the energy supplied is limited.
- If the energy supplied by the system ($E_{GRID,h}$) exceeds the ESS inverter power ($P_{IN,BAT}$) the energy in ESS ($E_{BAT}$) turns to be the energy in previous hour ($E_{BAT,h-1}$) summed to hourly photovoltaic production ($E_{PV,h}$) minus the ESS inverter power ($E_{IN,BAT}$).
- If the state of charge in the previous hour ($E_{BAT,h-1}$) summed to the energy balance in the current hour ($-E_{GRID,h}+E_{PV,h}$) is lower than the minimum storage

capacity, the battery is totally discharged and the SOC is 10%.

- Without restrictions, the energy in the storage system is the result of adding the energy in the previous hour summed to the photovoltaic production ($E_{PV,h}$) minus the energy supplied ($E_{GRID,h}$).
- To guarantee the calculation of annual data under the same conditions, every year a virtual reset is made to the SOC of the batteries.

Therefore, according to the algorithm shown in Fig. 3, iterations are performed for an ESS size between 0 and 6000kWh. Lithium batteries are selected and thus, a depth of discharge of 90% are selected, as well as the battery self-discharge rate (σ) of 0.05, the efficiency of the inverter ($\eta_{INV}$) of 0.95 and the efficiency of the BESS ($\eta_{BAT}$) of 0.92.

The charging and discharging patterns of the storage system are usually periodic since the photovoltaic production ($E_{PV}$) has a daily periodicity and the energy to be supplied ($E_{GRID}$) is constant. However, as shown in Fig. 4 for the simulation period between hours 104 and 113, the photovoltaic production ($E_{PV}$) is much lower than that of the previous day whose simulation period is between hours 80 and 89. Since the SOC of the storage system is high (65%) when photovoltaic production is reduced, it does not affect the constant power that is intended to be delivered. Therefore, it is vital to have a storage with an inertia that can maintain constant power not only at night, but on those specific days of low photovoltaic production. That is why a high capacity storage system will have fewer energy deficits. If the SOC is high and more energy is produced than the constant power command to be supplied, as in the period of hours 87 and 88, an energy surplus occurs and the power cannot be kept constant.

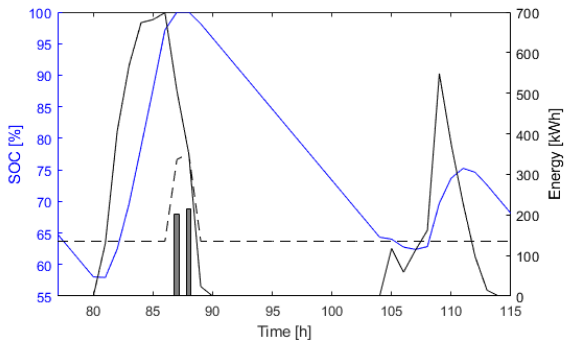


Figure 4. Variation of SOC and energy deviations

Due to the conditions imposed in this Section, the power supplied cannot always be kept constant. Fig. 4 shows the evolution of the SOC in the ESS for several days, and by means of this graph four representative time intervals can be distinguished.

- The first interval (I) corresponds to the range of [53h-56h]. Within this interval, the ESS is completely discharged and $E_{PV,h}$ is insufficient to supply constant $E_{GRID,h}$.
- The second interval (II) corresponds to the range of [56h-60h]. Within this interval the SOC of ESS increases since the storage system is unrestricted and $E_{PV,h}$ is greater than the constant $E_{GRID,h}$.
- The third interval (III) corresponds to the range of [60h-64h], where the ESS is fully charged and $E_{PV,h}$ is greater than $E_{GRID,h}$. Therefore, the system cannot keep the power supply constant and the surplus of energy is dumped into the grid.
- In the fourth interval (IV), with hours belonging to [64h-72h], the SOC of ESS decreases since the storage system becomes unrestricted and $E_{PV,h}$ is lower than $E_{GRID,h}$.

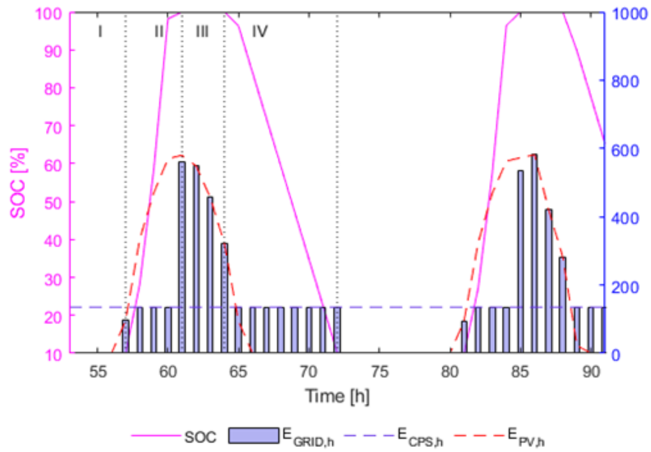


Figure 5. SOC evolution and energy balance in ESS.

By performing this analysis, different sizing criteria defined by ranges of CPO, ESS sizes and NEC cycles will be extracted depending of constant power setpoint. The multiple iterations of hourly energy balance in a long simulation period guarantee a significant mean of the performance of the system.

## 3. Case study

The objective of this case study is to select the optimal sizing parameters for the PV-ESS installation, under the ESS management algorithm shown in Section 3.2. Therefore, in this section the objective is to present the main dynamics of the model under the ESS management algorithm of section 3.2.

The proposed photovoltaic installation has 1MWp, South oriented in a fixed plane (35 degrees) and located in Zaragoza (Spain) and it is chosen with a temperature coefficient of 0.0038ºK-1 typical for monocrystalline photovoltaic panels.

### 3.1. Annual constant power setpoint (ACPS)

The annual constant power setpoint (ACPS) is explored in order to extract sizing criteria that can relate the annual CPO factor to the S2P and NEC of ESS for a wide range of Wp of photovoltaic installation. These criteria will be extracted attending to the AED and AES levels and the number of equivalent hours of the mentioned indices.

The AED and AES indices shown in Fig.6, respectively, represent the average of AED, and AES indices for the 11 years of simulation. It will be useful to select an optimal energy storage system. In general, a negative slope is observed initially in all the graphs since AED and AES levels decrease as the S2P increases. However, there is a critical S2P from which the increase of S2P does scarcely contribute to the reduction of AED or AES. From that critical S2P on, there is no point in increasing the S2P, as the AED or AES reduction is negligible compared to the reduction observed for lower S2Ps.

In Fig. 6, the dashed line joins the elbows of the different CPO factor curves, indicating the advisable minimum battery capacity that should be selected for each CPO factor. Selecting an AED less than 5% means the same as guaranteeing a system firmness or credit capacity of 95%. According to Fig.6, to maintain the capacity credit of 95%, the storage capacity increases proportionally with the CPO factor, for CPO factor values lower than 0.1 (CPOf = 0.02 imply an S2P = 0.3, CPOf = 0.06 imply an S2P = 0.9 , CPOf = 0.08 imply an S2P = 1.25). In turn, for CPO factor values up to 0.1, the dashed line is above the CPO curves indicating that the required battery size must be increased exponentially (CPOf = 0.12 imply an S2P = 2.9, CPOf = 0.14 imply an S2P = 4.55 ). For CPO factors greater than 0.14, it would not be appropriate to guarantee a capacity credit of 95% due to the oversizing of batteries that is necessary (S2P> 6).

For example, according to Fig.6, to guarantee an AED lower than 5% with a CPO factor up to 0.14, an S2P of at least 4.6 must be chosen to cover that CPO factor (i.e, deliver 140kW in a constant way many hours of the year). As mentioned in the previous section, the maximum value of the average capacity factor (CFPV) in a photovoltaic installation was discussed in the previous section, which is 0.188

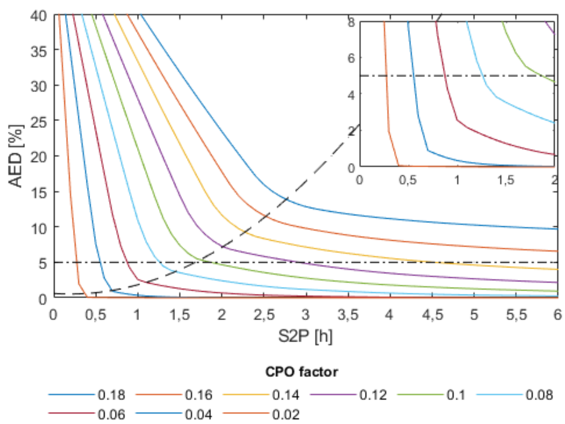



Figure 6. Annual Energy Deficit (AED) as a function of the ratio S2P and Constant Power Operation Factor for annual constant power setpoint

In Zaragoza, a 1MWp PV plant with a S2P of 1.9 (1.9MWh of capacity) can deliver a constant power of 100kW (CPO factor of 0,1) the 95% of the hours of the year (AED lower of 5%).

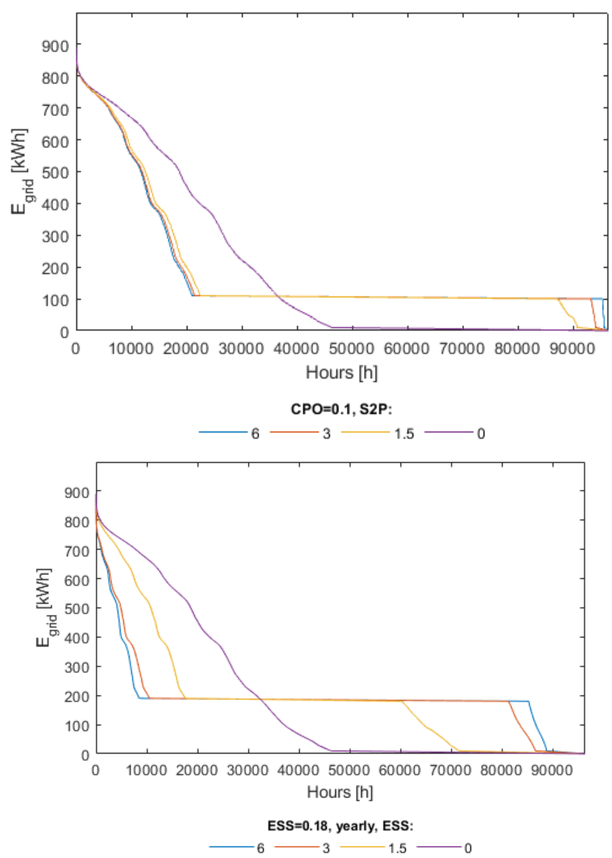
### 3.2. Generation duration curves (GDC) comparative

The GDCs obtained in this section allow to analyse the availability or use capacity of the system. For the simulations carried out, the vertical axis represents the hourly energy available to be delivered to the electric grid (EGRID) and the horizontal axis represents each of the hours of the simulation period (8760 hours x 11 years).

In Fig. 7a several simulations are superimposed varying the storage capacity for an intermediate factor CPO of 0.1. Increasing S2P from 1.5 to 6 implies a reduction in energy deficits in the system, going from guaranteeing a constant power of 87000 hours (90.3% of the time) to 96000 hours (99.6% of the time), which is practically the entire simulation period. However, this increase in S2P does not imply a reduction in energy excesses with respect to the constant power reference. For at least 20000 hours (20.7% of the time), the energy supplied to the grid is higher than the power setpoint. As already mentioned in Section 1, if an excess of energy supplied to the grid could imply penalties, the use of a strategy that reduces photovoltaic production by modifying the operating point of the photovoltaic inverter would guarantee constant power in the period in which is obtained surplus energy (timeframe 0-20000h).

In a similar way, in Fig. 7b the simulations are superimposed for a high CPO factor of 0.18 that is close to the maximum that a photovoltaic plant can supply as calculated in Eq. (1). As the constant power requirement to supply is higher than the previous simulation, for S2P of 1.5, constant power can only be guaranteed for 60000 hours (62.3% of the time). However, increasing S2P to 6, the constant power can be covered for 88000 hours (91.3% of the time). Therefore, for a high value of CPO factor, increasing the storage system implies significantly increasing the number of hours in which constant power can be supplied since deficits are reduced. In addition, for a high CPO factor in which the storage is increased, it is possible to slightly reduce the energy excesses.

A common factor in both simulations is that increasing the storage system implies a significant reduction in energy deficits in the system. However, excess energy is less affected.




Figures 7a and b. Load duration curves with fixed CPO factor, varying thre ratio between the storage capacity S2P and the peak power

3.3. Contour lines

Figure 8 shows the number of annual hours of energy deficit with respect to the power setpoint. The contour line graph is a function of S2P and CPO factor.

With the aim of extracting a more comprehensive impact of the design criteria, the mentioned number of equivalent hours represent a fine adjustment to quantify for a given CPO factor and from a specific S2P on, the number of hours within a year for which the firm PV plant does not reach the CPO factor. Selecting the area above the 441-hour red contour curve in Fig. 8 guarantees a system firmness or credit capacity of 95%.

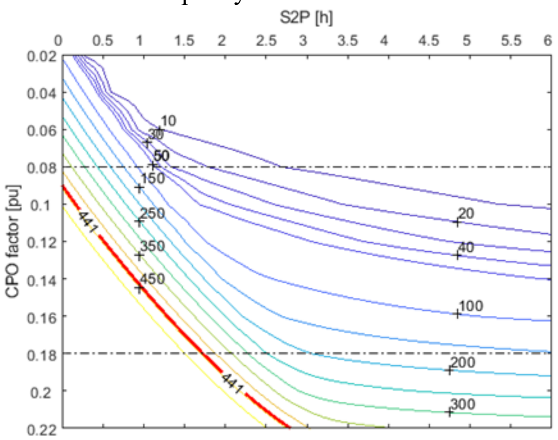



Figure 8. Annual number of hours of energy deficit with respect to the setpoint value. In red the contour curve that guarantees a capacity credit of 95%.

## 4. Conclusion

Batteries are a fundamental element linked to the great development and penetration of solar photovoltaic energy that is expected in the coming years. This paper presents different useful parameters to determine the size of the energy storage system and the operation strategy for guarantee a certain value of capacity credit.

Useful curves are presented for this sizing and operation decision. For example, it has been shown that to reduce energy deficits with respect to a constant power setpoint, a CPO factor range from 0.02 to 0.16 would lead to values of ratios between the capacity of the storage and the peak power of the pv system up to 2. Storage is not the most effective option to reduce the energy excesses with respect to said setpoint. On the other hand, increasing the storage capacity values, although they require a higher initial investment, means a better treatment of the battery and therefore reduces its aging, thus lengthening its lifetime.

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