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Unfavourable scenario analysis of compensation mechanisms for excess energy in self-consumption photovoltaic installations in the Spanish residential sector

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Abstract.

Self-consumption photovoltaic installations in the residential sector have great potential to mitigate the emissions associated with the current high consumption of fossil fuels. However, few studies analyse the technical and economic performance of these installations as a function of the electricity tariff contracted by the prosumer.
This study provides a first approach to this idea, as well as analysing an emerging tariff in the Spanish electricity market, such as the virtual battery (solar piggy bank or net billing), which allows the entire bill to be offset with photovoltaic surpluses.
A technical-economic analysis of a self-consumption photovoltaic installation connected to the grid is carried out for different peak power values, as well as for different consumption profiles and different electricity tariffs.
The results show the importance of considering the prosumer's consumption habits, as these directly influence the performance of the installation. Thus, it is not possible to obtain a single optimal solution for all cases. Among other conclusions, it was found that for surplus-to-consumption ratios in the range of 130-180 % and above, the virtual battery tariff is the best economic option.

Key words.

Photovoltaic solar energy, prosumer, self-consumption, net metering.

1. Introduction

Currently, fossil fuels dominate the global energy system, accounting for more than 80% of the total energy supply [1]. A transition towards an energy model based on renewable energies is therefore essential. Along these lines, action on buildings is an excellent opportunity to reduce energy consumption, as energy demand in buildings exceeds one-third of the world's final energy consumption and is responsible for around 40% of total global CO_2 emissions [2,3].

In this context, renewable energies take on special relevance, as they represent a great alternative to reverse the current energy model, based on fossil fuels [4,5], which is one of the keys to tackling the existing problem of climate change [6]. Of all the renewable technologies, solar photovoltaic energy has experienced the greatest growth in recent years, which has been accentuated by the ease of integration of this technology in the residential sector and its high economic return compared to the level of risk [7,8]. During 2022, solar photovoltaic technology has followed the same trend as in previous years, i.e., standing out from other renewable technologies as the one that has increased the most, incorporating 4,498 MW to the national generation park, which has meant an increase of 29.4% over the previous year [9]. At the same time, Spain is consolidating its position as a world leader in solar energy, ranking first in the world in terms of the percentage of solar energy in the electricity supply, with a value of 19.1% [10].

One of the main agents in this energy structure is the electricity market. In Spain, electricity supply activities are carried out by different parties, such as electricity producers, the market operator, the system operator, the transporter, distributors, marketers, consumers, storage facility owners, independent aggregators, and renewable energy communities [11,12]. Generation and commercialisation activities are liberalised, thus allowing for greater competition in the market. However, transmission, distribution and operation activities are not.

In the national regulations related to this area, novel concepts are introduced, such as the improvement of the economic conditions of prosumers (those who are both producers and consumers) [13,14] and the modality of self-consumption, which can be without surpluses (energy cannot be discharged to the grid) or with surpluses (energy can be discharged), among others. However, one of the most significant concepts included in this regulation is the simplified surplus compensation mechanism. This mechanism consists of a balance in economic terms of the energy consumed in the billing period, although the power term cannot be compensated [15].

In this paradigm, electricity retailers play an important role, offering a wide range of tariffs. In Spain, there are 742 electricity retailers, grouped into the free market and the regulated market [16]. The regulated market suppliers are also called reference suppliers and there are eight of them [17]. These marketers are characterised by offering a single tariff, the Voluntary Price for Small Consumers (PVPC) tariff, which establishes a different price for the purchase and sale of energy for each hour of the year. This tariff is regulated by the Spanish Government, which regulates the margins of the suppliers. On the other hand, the free-market suppliers are very varied and there is a great deal of competition between them, for the liberalisation of the electricity supply business. Within the framework of the free market, several suppliers offer virtual battery services or tariffs or solar piggy banks, which carry out "net billing" as far as the surplus compensation mechanism is concerned. This mechanism allows the user the possibility of carrying out an unrestricted balance in each billing period, in which if the economic valuation of the surplus energy is higher than the economic valuation of the energy taken from the grid, this balance can be accumulated in a virtual battery or solar piggy bank, to which a balance can be added or deducted in subsequent months, as appropriate. If this balance is sufficient, it can also be used to compensate for the power term of the bill, and the entire electricity bill can be compensated in this way.

Following the above, the main objective of this work is to carry out an analysis of the technical-economic performance of self-consumption photovoltaic installations connected to the grid in a series of single-family homes after the application of the most representative tariffs among those existing in the Spanish electricity market in a very unfavourable energy cost scenario, such as the year 2022, in which energy costs soared due to the geopolitical tensions existing on the world scene derived from the war between Russia and Ukraine. The analysis of this unfavourable cost scenario is intended to serve as a reference for possible future situations.

2. Materials and methods

The methodology followed for the analysis is structured in different sections.

A. Sample characterisation

The technical and economic performance of the different tariffs has been analysed in a series of single-family dwellings with heterogeneous consumption, whose main characteristics are shown in Table I.

Table I. – Analysed dwellings

ID	Type	P_c (kW)	CP (kWh)
DET 1	Detached	5.75	9,306.52
DET 2	Detached	3.30	4,595.49
DET 3	Detached	3.30	1,259.24
DET 4	Detached	4.60	5,030.97
DET 5	Detached	4.00	2,486.84
DET 6	Detached	3.45	1,174.58

B. Obtaining the consumption profile

Prosumer consumption data were obtained directly from the distribution companies, with consumption profiles being perfectly defined for the 8,760 hours of the year (CP_i). It should be noted that the variable i represents the hours of a year and therefore takes values from 1 to 8760. This is possible when evaluating existing buildings and thanks to the current existence of smart meters, which can provide hourly or quarter-hourly data.

C. Pre-dimensioning of the system

This step consists of deciding whether to maximise energy production (annual or daily) or self-consumption, a decision that will influence the parameterisation of the installation, in particular the orientation and inclination of the installation.

D. Obtaining the energy production of the system

The annual hourly energy production for a 1 kWp photovoltaic system is determined below ($E_{1\,kWp,\,i}$). For this purpose, the Photovoltaic Geographical Information System (PVGIS) tool developed by the European Union was used to calculate the energy production of a photovoltaic installation located in any area of Europe, Asia, and America, thanks to the extensive solar radiation database implemented in the software.

The energy production of the desired installation ($E_{total,\,i}$) is calculated according to Eq. (1), by multiplying the energy production of an installation of the same characteristics, but of a size of 1 kWp by the desired peak power (P_p).

$$E_{total,i} = E_{1\ kWp,i} \cdot P_p \qquad (1)$$

In this way, the consumption and production values are obtained for all the hours of the year, which will then be matched to carry out the different energy balances that will evaluate the performance of the system.

E. Energy analysis

A precise energy analysis has been carried out for the 8,760 hours of the year.

Thus, the energy taken from the grid ($E_{grid,\,i}$), is defined as the difference between the consumption (CP_i) and the production of the installation ($E_{total,\,i}$) when the consumption is greater than the production, or in other words, when the photovoltaic production is not capable of supplying the user's consumption by itself. If the production is greater than or equal to the consumption, the energy taken from the grid equals 0. This relationship is reflected in Eq. (2).

$$If\ CP_i > E_{total,i}\,;\ E_{grid,i} = CP_i - E_{total,i} \qquad (2)$$

On the other hand, surplus energy ($E_{e,\,i}$) is defined as the difference between PV production ($E_{total,\,i}$) and consumption (CP_i) when production is greater than consumption, as indicated in Eq. (3), which has been particularised for the case of this study.

$$If\ E_{total,i} > CP_i\ ;\ E_{e,i} = E_{total,i} - CP_i \quad (3)$$

Directly related to these two previous parameters is the self-consumption (SC_i), which refers to the energy saving that the direct use of the energy generated by the installation entails. Self-consumption is evaluated in two situations: the first, when consumption is greater than production (in this case, self-consumption will be equal to production), and the second, when production is greater than consumption, in which self-consumption is equal to the user's consumption. These conditions are reflected in Eq. (4) and Eq. (5).

$$If\ CP_i > E_{total,i}\ ;\ SC_i = E_{total,i} \quad (4)$$
$$If\ E_{total,i} > CP_i\ ;\ SC_i = CP_i \quad (5)$$

From the previous magnitudes, calculated hour by hour, the annual sums are obtained. *CP* refers to the annual sum of the user's consumption, E_{total} to the total energy generated by the installation in the year and E_{SC}, E_{grid} y E_e to the annual sums of self-consumed, grid-consumed, and surplus energy, respectively. These expressions are shown in Eq. (6) and following.

$$CP = \sum_{i=1}^{8760} CP_i \quad (6)$$
$$E_{total} = \sum_{i=1}^{8760} E_{total,i} \quad (7)$$
$$E_{SC} = \sum_{i=1}^{8760} SC_i \quad (8)$$
$$E_{grid} = \sum_{i=1}^{8760} E_{grid,i} \quad (9)$$
$$E_e = \sum_{i=1}^{8760} E_{e,i} \quad (10)$$

Once these annual values have been calculated, it is possible to obtain different ratios that evaluate the energy performance of the installation, such as self-consumption, surpluses or the energy required to be taken from the grid, and the relationships between them. Self-consumption (*SC*) indicates what fraction of the installation's energy production is used directly to supply consumption. There is some disagreement in the definition of this value, but it is possible to define it also as what part of the total consumption of the prosumer is directly provided by PV production. Several studies show the importance of optimising this parameter by modifying the prosumer's consumption habits as a key factor in maximising the performance of the installation. *Excess* is the fraction of the installation's energy production that cannot be used directly, and which is discharged into the grid to obtain the corresponding economic compensation. Grid energy (*Grid*), i.e. the energy that cannot be supplied by the PV system due to a lack of production and which must be supplied from the grid. Finally, the ratio between surplus and user consumption ($Excess_c$), is a value that is relevant for the analysis of the results. The corresponding expressions are given in Eq. (11) and the following.

$$SC = \frac{E_{SC}}{E_{total}} \quad (11)$$
$$Excess = \frac{E_e}{E_{total}} \quad (12)$$
$$Grid = \frac{E_{grid}}{CP} \quad (13)$$
$$Excess_c = \frac{E_e}{CP} \quad (14)$$

F. Economic analysis

This economic analysis includes two very significant parameters, such as the payback time and the annual economic balance, which refer to the number of years in which the initial investment is recovered and the amount that the prosumer will pay to the retailer in the year, respectively.

To carry out this analysis, a search of the existing tariffs in the electricity market was carried out. It was decided to include five tariffs in the analysis: four corresponding to the free market (including the three suppliers with the largest market share in the free market) and one corresponding to a supplier offering virtual battery (VB) services. The last tariff analysed corresponds to the tariff regulated by the Spanish Government (regulated market). A summary diagram is shown in Table II.

Table II. Summary of electricity tariffs

Market type	Tariff	Energy consumed	Excess energy
Free	FM1	Flat-rate electricity price	Stable price
	FM2	Flat-rate electricity price	Stable price
	FM3	Stable price	Stable price
	VB	Flat-rate electricity price	
Regulated	RM	Flat-rate electricity price	

The FM1, FM2, VB and RM tariffs set hourly energy prices, i.e. prices that vary according to the time of day at which energy is consumed. The VB and RM tariffs offer 24 energy cost values per day, i.e. one value for each hour. They have the advantage that there are times of the day when energy has an extremely low value, so if the consumer can bring his consumption to these times of the day, he will be able to obtain his energy at a very low cost. On the other hand, the FM3 tariff offers a stable price for the energy consumed.

In this way, by matching hour by hour the costs of purchase, $C_{energy,\ i}$, and sale, $C_{excess,\ i}$, of energy with the user's consumption, it is possible to obtain the economic returns derived from the corresponding energy balances, such as the savings from self-consumption, $C_{SC,\ i}$, the cost of energy taken from the grid, $C_{grid,\ i}$ and the amount obtained from the compensation of the surplus energy, $C_{e,\ i}$. It is also important to calculate the cost of energy before the PV installation, $C_{c,\,i}$, since this cost will be used, after incorporating the cost derived from the power term, to calculate the savings obtained after the installation has been implemented. The expressions governing these variables are presented in Eq. (15) and the following.

$$C_{SC,i} = C_{energy,i} \cdot SC_i \qquad (15)$$
$$C_{grid,i} = C_{energy,i} \cdot E_{grid,i} \qquad (16)$$
$$C_{e,i} = C_{excess,i} \cdot E_{e,i} \qquad (17)$$
$$C_{c,i} = C_{energy,i} \cdot CP_i \qquad (18)$$

As in the energy analysis, it is necessary to obtain the annual values, which are given in Eq. (19) ff.

$$C_{SC} = \sum_{i=1}^{8760} C_{SC,i} \qquad (19)$$
$$C_{grid} = \sum_{i=1}^{8760} C_{grid,i} \qquad (20)$$
$$C_e = \sum_{i=1}^{8760} C_{e,i} \qquad (21)$$
$$C_c = \sum_{i=1}^{8760} C_{c,i} \qquad (22)$$

After applying the power term, the total cost before PV, $C_{tot\ without\ PV}$, and the total cost after PV, $C_{tot\ PV}$ are obtained. P_c, n, $C_{p,\,peak}$ and $C_{p,\,off-peak}$ refer to the contracted power, the number of days in the billing period, the cost of power in peak period and the cost of power in off-peak period, respectively. Eq. (23) and Eq. (24) show the expressions used.

$$C_{tot\ without\ PV} = C_c + P_c \cdot n \cdot \left(C_{p,peak} + C_{p,off-peak}\right) \qquad (23)$$
$$C_{tot\ PV} = C_{grid} - C_e + P_c \cdot n \cdot \left(C_{p,peak} + C_{p,off-peak}\right) \qquad (24)$$

Once all these parameters have been defined, it is possible to calculate the economic ratios that evaluate the installation, such as the investment to be made, I, the annual savings obtained, S, and the payback time, PB, calculated as the ratio between the initial investment made and the annual savings obtained. Note that C refers to the unit cost of the PV system [€/kWp]. Eq. (25) and subsequent ones set out the expressions governing these variables.

$$I = P_p \cdot C \qquad (25)$$
$$S = C_{total\ without\ PV} - C_{total\ PV} \qquad (26)$$
$$PB = \frac{I}{S} \qquad (27)$$

3. Results

The results presented here correspond to one of the dwellings analysed, namely dwelling DET 4.

Fig. 1 shows for each of the five tariffs analysed and described above, FM1, FM2, FM3, VB and RM, the total cost before photovoltaic installation, i.e. the amount that the user would pay to the supplier annually for the power and energy terms.

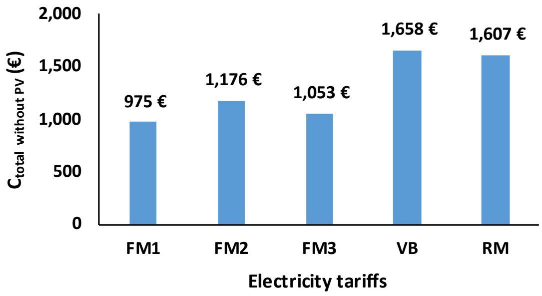

Fig. 1. Total cost without PV (DET 4)

It is possible to observe that the FM1 tariff has the lowest value. This is because this tariff offers energy at a lower cost than the others. On the other hand, the VB tariff, i.e. the tariff that allows net metering, showed the highest cost value for all dwellings, which is in the range of 50% - 90% higher than the cost associated with the FM1 tariff. The wide difference between the two extreme values of the range is directly related to the consumer's consumption habits, i.e. the hours at which he/she consumes energy. The VB tariff offers energy at a higher cost than the others, penalising this considerably by not having a self-consumption photovoltaic installation.

On the other hand, Fig. 2 shows a stacked column graph that can be used to compare the different tariffs analysed, particularly for the DET 4 house and a 3 kWp photovoltaic installation.

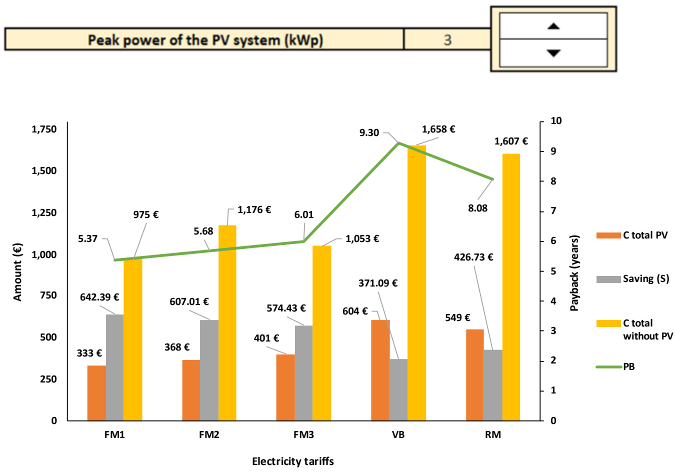

Fig. 2. Economic data for a self-consumption PV system (DET 4, 3 kWp)

For the specific case presented (DET 4, 3 kWp), it can be deduced that the FM1 tariff is the optimal solution, as it yields the best economic results. The annual savings are the highest of all (642.39 €). At the same time, the total cost after PV (333.02 €) and the payback time (5.37 years) are the lowest. As there is not a large amount of surplus, the main advantage of the VB tariff is not evident, resulting in less competitive economic returns, as can be seen in the figure.

On the other hand, it is clear from this case that it is not possible to optimise all the variables at the same time, so it is necessary to choose which of them to prioritise. If one wants to maximise the return on the initial investment, i.e. to obtain a low payback, these are yielded by the FM1, FM2 and FM3 tariffs for small values of installed power. In this case, the prosumer should leave aside the optimisation of the total cost after PV. However, if the amount to be paid to the supplier is to be reduced to a minimum, it is necessary to relegate the payback to a secondary level, since through the VB tariff it is possible to have invoices with 0 cost, but with large installation sizes, which considerably increases the initial investment and, therefore, penalises the payback.

Fig. 3 shows the final cost that the user will have to pay to the different suppliers for the whole year after having a self-consumption photovoltaic installation. A sweep of peak power has been made from 1 (small installations) to 10 kWp (above this value they are considered oversized in the residential sector). The ratio between surplus and user consumption is also shown for each of the peak power values.

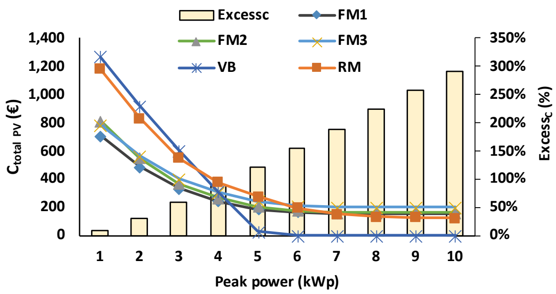

Fig. 3. Total cost PV (DET 4)

It can be seen that for *Excess*$_c$ values in the range of around 130-180 %, the VB tariff begins to stand out from the others as the offer that provides the highest economic return. This is because, once this value is reached, the surpluses are so high that they make possible the total compensation of the energy term, in addition to that of the power term. However, for small values of this ratio, it is not worth contracting this tariff, since, as there are not enough surpluses to compensate for the terms indicated above, the additional costs imposed by this supplier in the costs of buying and selling energy (0.01 and 0.005 €/kWh, respectively), as well as in the monthly fee (4 €/month), penalise the choice of this tariff.

It is also possible to observe that, in the offers of the retailers in which simplified surplus compensation is applied, i.e. in the FM1, FM2, FM3 and RM tariffs, a horizontal asymptote is reached that stabilises its value in the annual cost of the power term. Once self-consumption savings and surplus compensation have been maximised, this is the minimum cost that would have to be paid to the corresponding marketer. Therefore, at this point, there is no interest in increasing the size of the installation, as the savings will remain constant, while the initial investment will increase considerably, which will penalise some economic terms such as payback time. This is the case when *Excess*$_c$ values of more than 200% are reached.

Finally, Fig. 4 shows the evolution of the payback (PB) for the same peak power sweep discussed above.

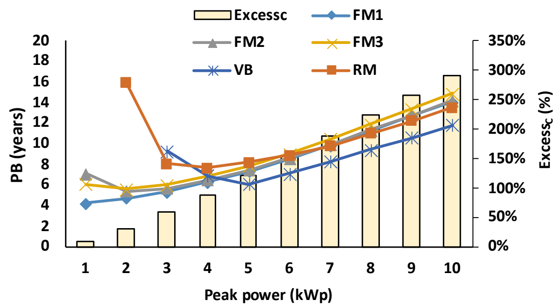

Fig. 4. Payback (DET 4)

While in some cases the representation of certain payback values that were unacceptable has been omitted, in others it has been retained to show the trend lines in their entirety. As with the previous variable ($C_{total\ PV}$), it can be seen that for *Excess*$_c$ values in the range of around 130-180 %, the VB tariff once again stands out from the others as the offer that provides the best result due to the advantages mentioned above.

4. Conclusions

This analysis has made it possible to evaluate the technical and economic performance of a grid-connected photovoltaic self-consumption installation in a very unfavourable cost scenario, depending on several parameters, such as the peak power of the installation, the user's consumption, the tariff selected and the surplus compensation mechanism to be used, among others.
The results showed a strong dependence of energy and economic performance on the user's consumption habits, i.e. it is impossible to obtain a one-size-fits-all solution. The optimal solution will vary depending on how and when the prosumer consumes energy and the variable to be optimised.

On the other hand, for small values of the *Excess*$_c$ ratio, which in most cases translates into small values of the installation's peak power, the VB tariff does not provide the prosumer with the best economic results, since as it does not have the large number of surpluses it is not possible to apply the main advantage offered by this virtual battery tariff, i.e. the additional compensation of the power term. This handicap is added to the extra cost imposed by this supplier on the costs of buying and selling energy. However, for values of this ratio within a range of around 130%-180%, this tariff begins to stand out clearly as the one that offers the highest economic return, whether this is evaluated from the point of view of the amount to be paid to the supplier in the year as a whole or from the point of view of the payback time.

It should be noted that this work opens up a wide range of possibilities for future analyses, such as example, the comparative analysis between virtual batteries and physical batteries. It is possible to think that the virtual battery will always be the winner as it does not have to make an initial investment, but it would be interesting to analyse the fact that the physical battery stores ordinary energy, the cost of which is substantially higher than the cost of surplus energy, which is the one that is compensated in the virtual battery tariffs. Also, a constant update of the tariff prices is foreseen, as this is a variable that is very susceptible to variations, especially considering the current global geopolitical situation.

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