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Impact of domestic PV systems in the day-ahead Iberian electricity market

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Abstract: The integration of residential photovoltaic (PV) systems for self-consumption is expected to unlock a variety of economic, technical and social benefits, such as the creation of local work and the reduction of the price of electricity, CO_2 emissions and electrical power losses in the transmission network. In spite of all these advantages, regulatory barriers prevented the development of renewable self-consumption in Spain prior to October 2018, when a new regulation introduced the right to self-consume electrical energy without charges. This work aims to estimate the effect of residential self-consumption on the Iberian electricity market. To achieve this goal, a ceteris paribus approach was adopted, the accumulated scattered PV self-production was turned into a reduction of the aggregate demand in the market and the new clearing point was established. Based on 2017 market data, the results showed that a 1% curtailment of the annual demand due to PV self-consumption could reduce the cost of the market-traded energy by almost 2%.

Keywords: renewable energy sources, photovoltaic systems, cost benefit analysis, supply and demand, prosumers, self-consumption, electricity markets.

List of Symbols

PV self-production – Dwelling	
PV peak-power capacity	P_{PV}, P_{PVp}
Hourly performance ratio (hour *h*)	PR_h
Hourly PV self-production (hour *h*)	$E_{PV\text{-}h}$
Wholesale market	
Traded energy	W_h
Clearing price	p_h
Cost of the traded energy ($C_h = W_h \cdot p_h$)	C_h
Wholesale market − PV self-production scenarios	
Reduction of aggregate demand due to PV self-production	$\Delta E_{SP\text{-}h} = E_{PV\text{-}h}$
Traded energy − PV self-production scenario	$W_{SC\text{-}h}(\Delta E_{SP\text{-}h})$
Clearing price − PV self-production scenario	$p_{SC\text{-}h}(\Delta E_{SP\text{-}h})$
Cost of the traded energy − PV self-production scenario	$C_{SC\text{-}h}(\Delta E_{SP\text{-}h})$
Variation of the traded energy	$\Delta W_h(\Delta E_{SP\text{-}h}) = W_h - W_{SC\text{-}h}(\Delta E_{SP\text{-}h})$
Variation of the clearing price	$\Delta p_h(\Delta E_{SP\text{-}h}) = p_h - p_{SC\text{-}h}(\Delta E_{SP\text{-}h})$
Variation of the cost of the traded energy	$\Delta C_h(\Delta E_{SP\text{-}h}) = C_h - C_{SC\text{-}h}(\Delta E_{SP\text{-}h})$

1. Introduction

Over the past decade, despite the economic-financial crisis which broke out in the US in 2007, the evolution of the investment in renewables has been able to continue growing steadily (IRENA, 2019). The successive and recurrent energy crises and the growing emphasis on the mitigation of climate change have contributed to a remarkable development of renewable energy (REE, 2019). Furthermore, a significant advancement can be witnessed in the production of electricity from renewable sources. This is particularly true for solar photovoltaic (PV) technologies, which has been rapidly declining in cost. For example, from 2010-2018, costs for PV systems decreased around 75% (REN21, 2019), as shown in Figure 1. The figure also shows the evolution of the annual traded energy and the mean price in the Iberian/Spanish wholesale electricity market for the same period (REE, 2011-2019). As can be seen, for the period 2010-2018, despite the reduction in demand due to the economic crisis, electricity prices in the Iberian/Spanish wholesale market have experienced a gradual growth, which makes residential PV systems increasingly attractive. Consequently, new actors such as prosumers (producers/consumers) are expected to play an important role, supported by the new regulation. Future scenarios of residential PV generation can change the current consumption profile in the wholesale market, since the energy produced and self-consumed locally is no longer withdrawn from the grid. As a result, the distributed PV self-production should lead to a contraction of the aggregate demand in the day-ahead market. As will be shown in Section 4, this will be especially significant for the central hours of the day, the higher PV production hours, which often are the more expensive time slots of the day.

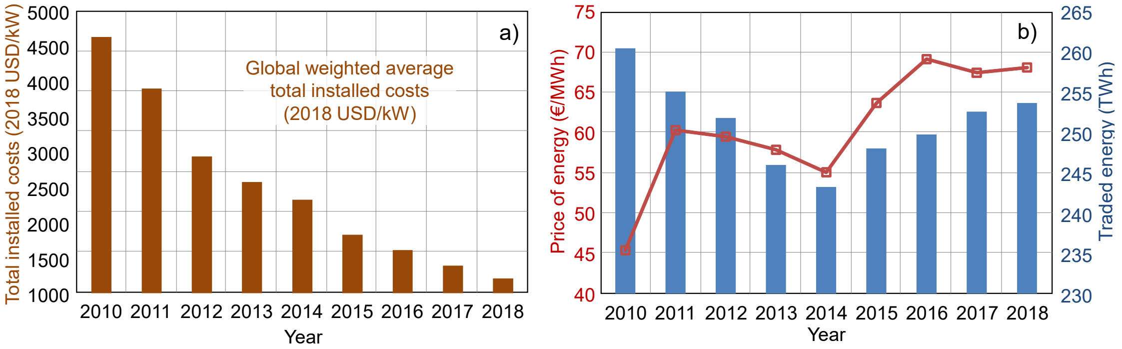

Figure 1. Evolution of the annual a) global weighted average total installed costs and b) traded energy and mean hourly price in the Iberian/Spanish wholesale electricity market

Most EU countries, aware of the benefits of self-consumption, have promoted policies in order to boost their development. For instance, Germany is the European country with the highest cumulative PV capacity (45.4 GW) and the strongest increase in PV generation (about 3 GW) in 2018 (IEA PVPS, 2018). Its feed-in tariff policy is the main driver of this growth. However, other countries such as Italy incentivise self-consumption by means of a net-metering scheme. In Portugal, since 2014, regulation has promoted self-consumption and the surplus electricity can be injected into the grid and is remunerated at wholesale market prices (Camilo, 2017). That regulation has been later updated in October, 25 2019, when the Portuguese Decree-Law no. 162/2019 was published. From January 1, 2020, self-consumption installations are regulated by the new rules. The new Portuguese legislation seeks to simplify licensing and the rules applied to self-consumption installations/facilities, which now can also share PV energy with neighbours and surrounding dwellings.

Rosales-Asensio et al. (2019) stated that, according to the judgement of energy policy experts, the absence of a stable regulatory framework and the existence of clear disincentives are the main reasons limiting the deployment of PV self-consumption in Spain. In 2018, new legislation aligned with this new paradigm was passed in Spain. The aim of the Royal Decree 244/2019 (RD, 2019) is to complete the regulatory framework for self-consumption promoted by Royal Decree-Law 15/2018 (RDL, 2018), which revoked the so-called *sun tax* (the payment of a backup charge, a grid-access charge and a generation tax, to selling the PV surplus energy to the grid by PV self-producers) previously in force, providing certainty and security to users. In particular, the new regulation develops the administrative, technical and economic conditions of self-consumption and introduces a simplified economic compensation mechanism to reduce consumers' electricity bills, offsetting their surplus of energy produced and not self-consumed.

The effect of utility-scale renewable electricity generation on market prices has been broadly analysed in the literature, since the sustained increase of wholesale electricity prices during the last decade in Spain and other countries of the EU has often been related to the costs of supporting the production of electricity from renewables. Nevertheless, this is only part of the story, since when some renewable production is dispatched in the wholesale market, an (approximately) equivalent amount of (more expensive) thermal generation is no longer necessary to meet the expected demand (Trujillo-Baute, 2018). Accordingly, the integration of renewables in the market puts a downward pressure on the market price, which, depending on the national energy policy, could be even stronger than the upward pricing pressure on consumers due to the renewable premium (extra payment to renewable generators in addition to the market price) (Trujillo-Baute, 2018; Sáenz de Miera, 2008; Burgos Payan, 2013). Peña and Rodríguez (2019) studied the feasibility and compatibility of the three Climate and Energy Package 2020 targets of the EU, focusing on the electricity prices of ten EU countries, including Spain. They found that *Increases in production from renewables decrease wholesale electricity prices in all countries*. Csereklyei, Qu and Ancev (2019) investigated the effect of wind and utility-scale PV electricity generation on wholesale electricity prices in Australia during 2010-2018, finding that an extra GW of dispatched wind capacity decreased the wholesale electricity price by 11 AUD/MWh for wind energy and by 14 AUD/MWh for PV. Pereira and Saraiva (2013) used a long-term system dynamics-based model to estimate the long-term evolution of the market price. This model was applied to the Iberian generation system, using different shares of wind power capacity to evaluate the impact of wind power on the Iberian day-ahead market price. They concluded that *as a result of the increasing penetration of wind power both in Portugal and Spain, the average market price tends to decline and the number of operation hours of traditional thermal technologies also gets reduced*. Antonanzas et al. (2017) analysed various day-ahead production forecasts for a 1.86 MW PV plant with different techniques and sets of inputs considered in order to estimate the market value of day-ahead forecasting.

The effect of residential PV self-consumption has also been a subject of study. The most recent research works have been centred on investigating the economic viability of residential PV systems under different regulations. For example, Camilo et al. (2017) investigated the economic profitability of different configurations of residential PV systems in Portugal. Their work particularly focused on the joint operation of self-consumption and battery storage. They concluded that self-consumption was already economically attractive, but storage was not a profitable solution, because the battery investment was still too high. Lopez Prol and Steiningera (2017) studied the implications of the recently repealed Spanish regulation on the profitability (internal rate of return) of potential residential, commercial and industrial investors. They also compared the previous Spanish regulation with alternatives such as net metering or net billing. They found that the previous regulation hindered the diffusion of PV grid-connected systems for self-consumption in Spain, since the regulation made them economically infeasible for average users of the residential (and industrial) segment. More recently, Roldán Fernández et al. (2020) assessed the profitability of residential PV self-consumption in Spain under the current regulation. They found that a 1.5–2 kW-peak PV commercial self-consumption kit yields to an optimum net billing situation for an average dwelling in Spain.

As can be seen above, the previous research can be classified into two broad categories:

- Research on the effects of utility-scale renewable generation on the wholesale market.
- Research on the economic viability of domestic (grid-connected) PV facilities.

Nevertheless, future scenarios of residential PV generation in Spain are expected to change the current demand profile in the wholesale market, since the energy produced and self-consumed locally is no longer withdrawn from the grid. Consequently, the aggregated demand will be contracted in the wholesale market.

Based on the hypothesis that this new regulatory framework is expected to favour the development of self-consumption and in order to take into account this crossed effect between cumulative PV self-consumption and the wholesale market, a new hybrid approach was adopted in this work. This study is mainly focused on the effect that the expected development of the Spanish domestic PV self-consumption would have on the day-ahead Iberian electricity market, the joint market for Portugal and Spain.

This study is of interest since a rapid deployment of domestic PV installations is expected over the next decade with the new regulation. The value of the analysis is reinforced by the fact that most previous research works have focused on the potential economic viability of PV projects with the old, now repealed, regulation (Lopez Prol and Steiningera, 2017). Since the legislative changes have been passed very recently in the Spanish parliament, this is one of the very first studies to analyse the expected effects of the new self-consumption regulation in the day-ahead Iberian market (mainly hourly traded energy and clearing prices).

2. Self-Consumption and Electricity Market in Spain

Studying the effects derived from the expected development of self-consumption scenarios on the day-ahead electricity market in Spain requires the knowledge and appropriate integration of two key elements: the actual market data and expected PV self-production. However, before calculating PV self-production and estimating how it will affect the market, it is useful to have an overview of the Iberian electricity market and the new regulation of renewable self-consumption in Spain.

2.1 The Regulation of Renewable Self-Consumption in Spain

The Directive (EU) 2018/2001 of 11th December 2018 (EU, 2018) on the promotion of the use of energy from renewable sources states that *with the growing importance of self-consumption of renewable electricity, there is a need for a definition of 'renewables self-consumers' and of 'jointly acting renewables self-consumers'. It is also necessary to establish a regulatory framework which would empower renewables self-consumers to generate, consume, store and sell electricity without facing disproportionate burdens.*

Consequently, points 14 and 15 of the Definitions section of the Directive defines both terms as follows:

- *Renewables self-consumer* means a final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self-consumer, those activities do not constitute its primary commercial or professional activity;
- *Jointly acting renewables self-consumers* means a group of at least two jointly acting renewables self-consumers in accordance with point (14) who are located in the same building or multi-apartment block.

For the purposes of this work, these definitions have been simplified as follows (avoiding the terms related to administrative and bureaucratic aspects):

- 'Renewables self-consumer' means a final customer who generates renewable electricity for their own consumption and who may store or sell the surplus self-generated renewable electricity. Our work is based on this type of customer.
- 'Jointly acting renewables self-consumers' or collective self-consumption, as it has been referred to in our work, in accordance with the Spanish regulation terminology, means a group of at least two jointly acting renewables self-consumers who are located in the neighbourhood of the renewable facility.

Self-consumption modalities provided in the new Spanish regulation can be summarized as follows:

- Self-consumption without an energy surplus (zero injection). In this case, the photovoltaic facilities contain elements necessary to ensure that the surpluses are not injected into the grid. Therefore, all the self-produced energy is consumed in the dwelling (perhaps it may be stored), so no energy is delivered to the grid.
- Self-consumption with an energy surplus (up to 100 kWp). When the generation facilities can supply energy for self-consumption and in addition, inject excess energy into transport and distribution networks. Hence, only a fraction of the self-produced energy is consumed (or stored) in the dwelling. The remaining energy is delivered to the grid.

  The simplified compensation mechanism of the energy surplus is a balance, in economic terms, between the cost of the energy consumed (purchased) and income of the energy delivered (sold) in the billing period. The value of the excess energy delivered to the grid is economically compensated in the consumer's invoice at the end of the billing period (one month).

2.2 The Iberian Electricity Market. An Overview

OMIE is the Market Operator of the Iberian Market, the joint European regional market for Portugal and Spain (OMIE, 2019). Around 80% of the total of the electrical energy produced in Spain and Portugal is exchanged in the day-ahead electricity market. The market is organized as a sequence of markets: the day-ahead market, the intraday market (with six sessions a day, close to real-time operation and a continuous European cross-border market) and the ancillary services market (as shown in Figure 2).

The daily market is composed of 24 hourly markets (auctions) which clear once a day. The purpose of the day-ahead market is to determine the electricity transactions for the following day. To achieve that goal, OMIE gathers bids from selling and buying agents, one day ahead of when these actual physical transactions take place (OMIE, 2019). There are hundreds of market agents and each of them can submit several bids to the market operator. Demand agents submit bids defining the amount of energy they want and the maximum price at which they are willing to buy that energy. These are called single bids.

In terms of the generation units (suppliers), their bids are elaborated by establishing the minimum price at which they are willing to produce energy. Generation units are also allowed by OMIE to include additional restrictions in their bids, called complex conditions, such as the indivisibility of blocks of energy, minimum income, scheduled stops and the load gradient.

Conditional on being dispatched, the price that producers receive or demand units pay is set equal to the highest accepted supply bid, the system marginal price. Since 2014, OMIE belongs to the Price Coupling of Regions (PCR), which is an initiative to develop a single price coupling solution to calculate electricity prices across Europe. Therefore, OMIE (2019) uses the welfare optimization algorithm called Euphemia (EPEX SPOT et al., 2016), which is compulsory by national regulation. This algorithm is a computationally expensive optimization algorithm that seeks to maximize the market's welfare. The welfare corresponds to the sum of the combined total of the gain from the purchase bids and the gain from the sale bids. For purchase bids, the gain refers to the difference between the price of the cleared purchase bids and the actual marginal price, while for sale bids, the gain corresponds to the difference between the marginal price and the price of the dispatched sale bids. The market operator has a maximum of only one hour to clear the 24 hourly slots of the day-ahead market to solve the optimization problem with the cited algorithm and provide a feasible solution, handling large amounts of data (market agents, bids and complex restrictions). The methodology used to reproduce the daily market under self-consumption scenarios will be presented in the next section.

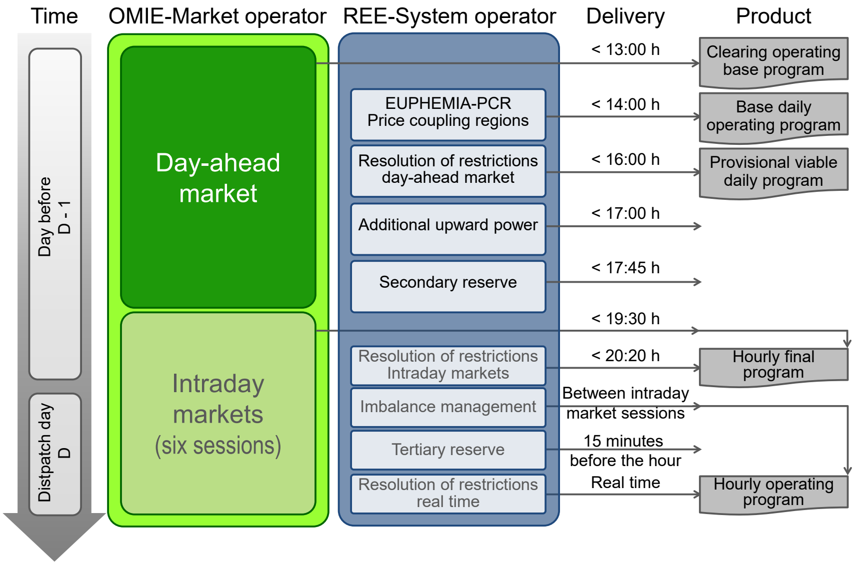

Figure 2. OMIE: The sequence of markets: the day-ahead market (OMIE), the intraday markets (OMIE) and the ancillary services markets (REE)

3. Materials and Methods

Data corresponding to year 2017 has been taken as reference in this work. Accordingly, the full hourly 2017 data-set corresponding to the Iberian day-ahead was retrieved from the web page of OMIE (OMIE, 2019), the Iberian/Spanish Market Operator. Analogously, the 2017 data-set of PV production in Spain was also retrieved from the public archive of Red Eléctrica de España (REE), the Spanish System Operator (REE, 2019).

Once the main sources of information used in this work have been specified, the following two subsections develop the details of the followed methodology.

3.1 Photovoltaic Generation Profile

Spain, due to its geographical location, is one of the EU countries with the highest amount of solar radiation. However, due to various political decisions, the development of PV production has been rather slow. According to IEA-PVPS (2018), the total accumulated capacity until 2017 was 4687 MW, of which only 236 MW (5.04 %) corresponded to self-consumption. Accordingly, PV facilities are expected to undergo significant growth in the coming years, favoured by the new regulation.

Although the new regulation includes various self-consumption options, this work focused only on self-consumption in a single-family house or semi-detached house. These consumers are likely to become self-consumers due to the ease of installation and because they do not require an agreement with other parties. Typical PV peak power kits available on the market are 0.5 kW, 1 kW, 1.5 kW and 4 kW (Camilo et al., 2017).

The total number of dwellings in Spain reached 25.21 million in 2011 (INE, 2019) (the last census available). Since then, the number of dwellings has remained almost constant, as shown in Figure 3 (MFE, 2019). Approximately 33.5% of these homes are houses (Eurostat, 2019). That means that in 2017, about 8.59 million houses could have included PV generation for self-consumption in Spain.

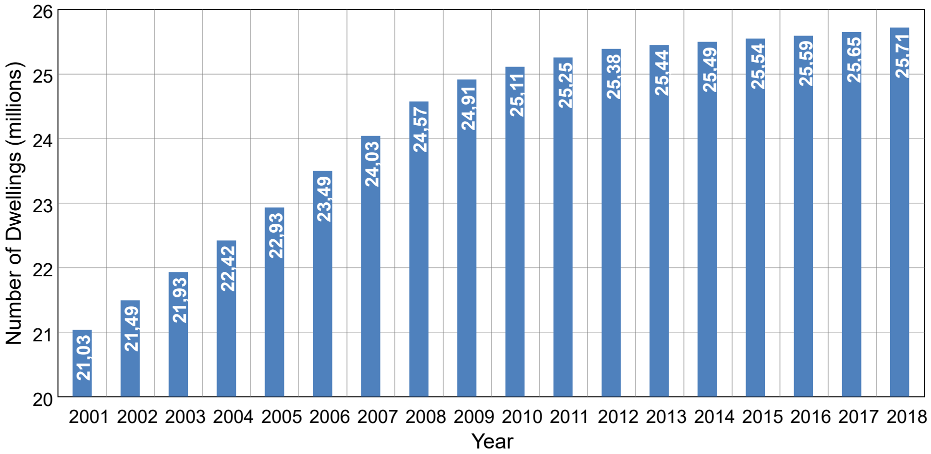

Figure 3. Evolution of the number of dwellings in Spain

A recent survey estimated that 16.4% of homeowners are considering installing PV panels (GAiE, 2019). The study concluded that around 328,000 Spanish homes could install a PV system in the next three years. It also predicted a PV installed capacity of 1500 MW at the end of the three-year period. The implementation of this 1500 MW of PV installation could require around 8,000 new specialized jobs: engineers, electricians, installers, auxiliary industry workers, maintenance or commercial personnel, among others (REM, 2019).

Once the number of houses with a PV system and the power of the PV systems have been assessed, the hourly generation scenarios can be set. For simplicity, different percentages of houses with an installed power kit of 1 kW were considered in this work. More precisely, two scenarios in which 15% and 30% of dwellings were considered to have a 1 kW PV self-consumption kit have been analysed. As already mentioned, these were conservative scenarios due to the low power of the considered PV kits and because collective self-consumption was not taken into account. The first 15% scenario roughly equals the number of owners who are already willing to install PV panels, according to the survey. Therefore, the total PV installed capacity considered in this work was 1256 MW of peak power for the 15% scenario and 2511 MW of peak power for the 30% scenario.

Regarding estimation of the PV generation, some researchers have calculated the energy output by assuming that PV panels are under country average conditions (López Prol and Steininger, 2017). In order to obtain a better estimate of the hourly PV energy production, both the effect of geographic and weather conditions have been considered. To fulfil that purpose, the hourly PV production of the considered scenarios was prepared from the actual recorded energy production data from existing PV installations in Spain. Since the public archive of Red Eléctrica de España (REE) provides the (Iberian aggregated) solar energy production, it is possible to retrieve this information for a better estimate of the PV resource. More precisely, in this work, the extrapolation of the hourly PV electrical production for the considered scenarios was conducted in two steps. First, the actual hourly generation profiles, elaborated from the retrieved information from REE archives for 2017 and the corresponding actually installed PV peak power capacity were used to calculate the hourly PV performance ratio of the Iberian system. The hourly performance ratio, PR_h, corresponding to the hour h, was defined as the ratio of the actual energy produced in that hour to the total installed PV power capacity:

$$PR_h = \frac{Actual\ PV\ plant\ output_h}{Installed\ PV\ power\ capacity_h} . \quad (1)$$

Secondly, the hourly PV production of the new scenarios was evaluated, taking into account the peak power capacity of the considered scenario and the corresponding hourly performance ratio. According to REE (2018), in 2017, the installed PV power capacity has remained invariable, around 4439 MW over the last few years (2013-2018). Figure 4 represents, for every hour of the day, the annual mean, maximum and minimum PV performance ratio (PR_h) for the analysed period (Peninsular Spain uses Central European Time). As can be seen in Figure 4, the maximum PR was reached at around 15:00 hours and peaked at just over 0.8 per unit, in line with the existing literature (Talavera et al., 2019).

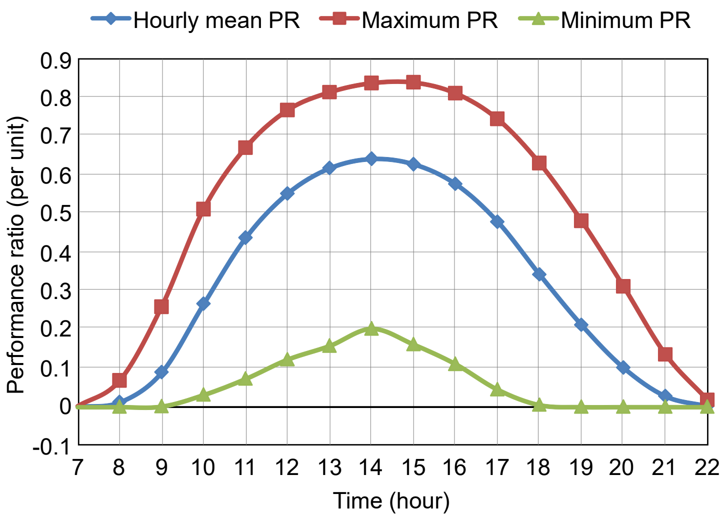

Figure 4. Annual mean values of the performance ratio, for every hour of the day, in 2017

Once the actual values of the PR_h were determined, the PV energy production, E_{PVhj}, for the hour h, corresponding to scenario, j, could be estimated through the product of the corresponding hourly performance ratio, PR_h, by the installed PV power capacity, P_{PVj}, corresponding to scenario j:

$$E_{PVhj} = PR_h \cdot P_{PVj} \quad (2)$$

3.2 Modelling the Influence of Self-Consumption on the Day-Ahead Electricity Market

Since this work is intended for rather long-term scenarios (one year) considering two different scenarios of installed PV power capacity, a simplified method was used to reproduce the day-ahead market. Several different approaches for daily market simulation have been considered in the literature, such as models based on artificial intelligence, linearization techniques or demand/generation curve algorithms. Artificial intelligence is used to measure the influence of renewable generation on the Spanish electricity prices (Azofra et al., 2015; Azofra, 2014). A simplified model, based on the linearization of the market around the clearing point, was utilized in (Müller and Jansen, 2019; Roldan-Fernandez et al., 2016a; Roldan-Fernandez et al. 2016b; Burgos Payan et al., 2013). Research based on a simplified market model using generation and demand curves can be found in (Roldán-Fernández et al., 2016c; Roldán-Fernández et al., 2017; Roldán-Fernández et al., 2018a; Ciarreta et al., 2014). The latter methodology has been adopted in this work. The historical archive of the Iberian market operator includes the details of market agents’ bids and is publicly available for free, with a delay of 90 days. In this work, this information has been used as a base for the considered self-consumption scenarios—more precisely, the information from the hourly merit-order generation and demand curves, corresponding to 2017, retrieved from the historical data available at the market operator’s web page (OMIE, 2019).

Figure 5 shows the aggregate generation and demand curves elaborated by the market operator for a specific hour. As can be seen, the market operator creates simple bid generation and demand curves from the simple bids (energy, price) submitted by the various market agents, sorting the bids of demand and supply agents by price in ascending order for generation bids and in descending order for demand bids.

Regarding the cleared generation and demand curves, these curves were obtained using the Euphemia algorithm, with the complex conditions of generation bids added. As a result, the dispatched generation and demand curves and the market clearing point (A in Figure 5 a)) were obtained.

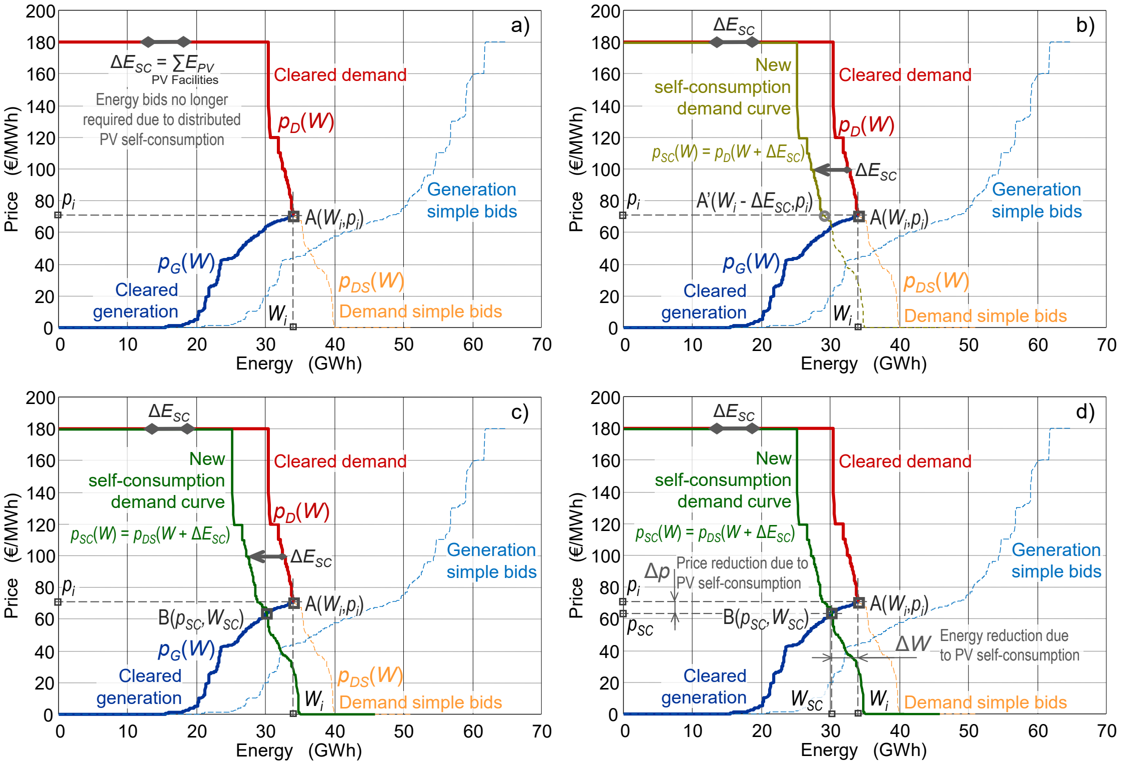

Figure 5. Example of one-hour data from day-ahead electricity market. Elaboration of the new self-consumption demand curve and determination of the new clearing point.

The energy bids corresponding to domestic self-consumers agents that will be no longer necessary due to self-consumption are located on the aggregate demand curve. As can be seen in Figure 5 a), as self-consumption avoided a certain amount of residential demand, the price considered for the avoided demand bids was 180.3 €/MWh; the maximum allowed in the Iberian market, because this is the instrumental price used by the agents of the domestic consumers to ensure their bids are cleared. Although these bids will be distributed throughout the initial flat part of the demand curve, for simplicity, in Figure 5 it has been considered that they are all join together.

Using this hourly data as a starting point, the cleared demand curve is modified (left-shifted) by reducing the energy bids in the amount, ΔE_{SC}, corresponding to the PV generation of the considered self-consumption scenario ($\Delta E_{SC\text{-}h} = E_{PV\text{-}h}$), as shown in Figure 5 b). As can be seen, the new demand curve, $p_{SC}(W) = p_D(W + \Delta E_{SC})$, finishes at point A’ therefore, there is no crossover point with the cleared generation curve.

Since the simple bid curve covers the full range of prices or energies and included the cleared curve ($p_D(W) = p_{DS}(W)\ \forall\ W \leq W_i$), to extend the demand curve from point A’ on the new demand curve is better based on the simple bid curve, $p_{SC}(W) = p_{DS}(W + \Delta E_{SC})$, as shown in Figure 5 c).

The new clearing point (B in Figure 5 d)) is then obtained as the intersection of the modified demand curve with the cleared generation curve. A broader description of the methodology can be found in (Roldán-Fernández et al., 2017).

When new market scenarios are developed, it is necessary to bear in mind that the bids of all the other agents will not change. Fortunately, that hypothesis of perfect market can be considered fulfilled (Sáenz de Miera et al., 2008; Roldán-Fernández et al., 2016c), since each market agent must elaborate their bids without knowledge of the bids of the other agents. This procedure was used for the 8760 hours of the year, allowing the new hourly clearing prices and traded energy for each of the considered PV self-consumption scenarios to be obtained. Hence, to better isolate the expected impact of the PV self-consumption on the day-ahead market, a ceteris paribus approach was adopted, enabling the accumulated scattered PV self-production to be turned into a reduction of the aggregate demand in the market and the new clearing point to be established.

As can be observed, PV self-consumption leads to a kind of *merit-order effect* in the wholesale market, which is similar to the merit-order effect of renewables in that it reduces the clearing price and the cost of the energy traded in the market, although it differs from renewables in which self-consumption reduces the amount of traded energy (Roldan-Fernandez et al., 2016a).

4. Results and Discussion

Once the methodology to reproduce the daily market under self-consumption scenarios has been described, the obtained results are presented. Subsequently, in the discussion subsection, we explore the underlying meaning of our findings.

4.1. Results of two PV self-consumption scenario analyses

This section presents the results of the two different scenarios of individual residential PV self-consumption in Spain, based on real market data corresponding to 2017 (retrieved from the public OMIE archive), which was taken as the base case. Figure 6 shows the registered hourly traded energy, W_h, and clearing price, p_h, corresponding to the 8760 hours of 2017 in the Iberian daily market (OMIE, 2019), where both daily (vertical) and seasonal (horizontal) variations can be observed.

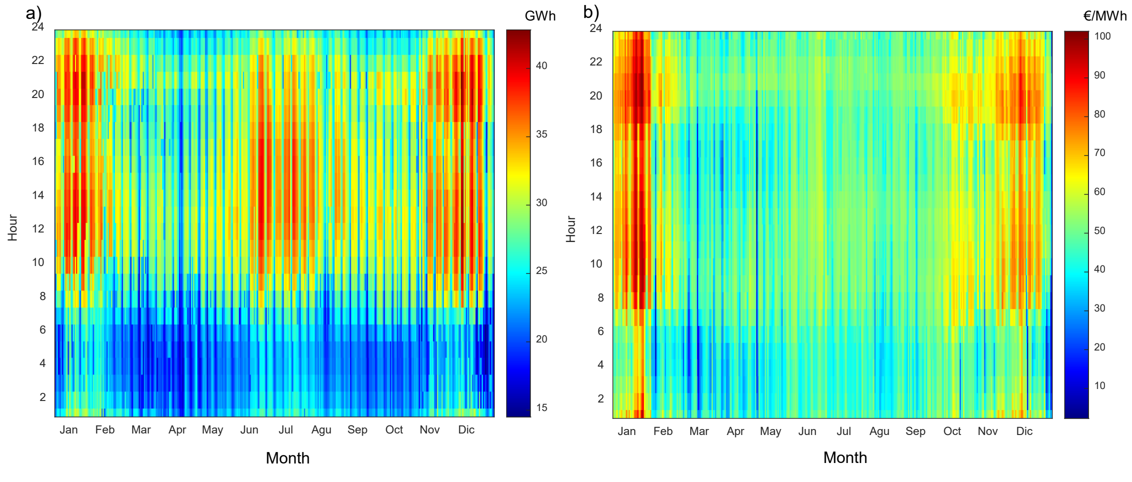

Figure 6. Values of a) traded energy and b) clearing price for each hour of 2017 in the Iberian day-ahead electricity market.

Two cases have been considered in this work:

- Scenario 1 (15% dwellings): 1256 thousand dwellings (detached or semi-detached houses) equipped with a PV generator kit of 1 kWp/dwelling
  - Total PV capacity: $P_{PVp} = 1256$ MWp
  - Total annual PV production for self-consumption: $\Delta E_{SC} = 2267$ GWh, 0.93% of the traded energy for the base case
- Scenario 2 (30% dwellings): 2511 thousand dwellings equipped with a PV generator kit of 1 kWp/dwelling
  - Total PV capacity: $P_{PVp} = 2511$ MWp
  - Total annual PV production for self-consumption: $\Delta E_{SC} = 4535$ GWh, 1.85% of the traded energy for the base case

In order to obtain plausible results, the scenarios analysed in this work were rather conservative, since only individual domestic self-consumption was considered. Moreover, a small commercial PV power kit of only 1 kWp per dwelling was considered, since, according to the National Commission of Markets and Competition (BIE, 2019), the mean value of the domestic contracted power (2.0 A tariff) was 4.03 kW in 2017. Figure 7 shows the Spanish PV self-production, $\Delta E_{sc\text{-}h}$, corresponding to each of the 8760 hours of 2017 for scenarios 1 and 2, where both daily and seasonal variations can be observed.

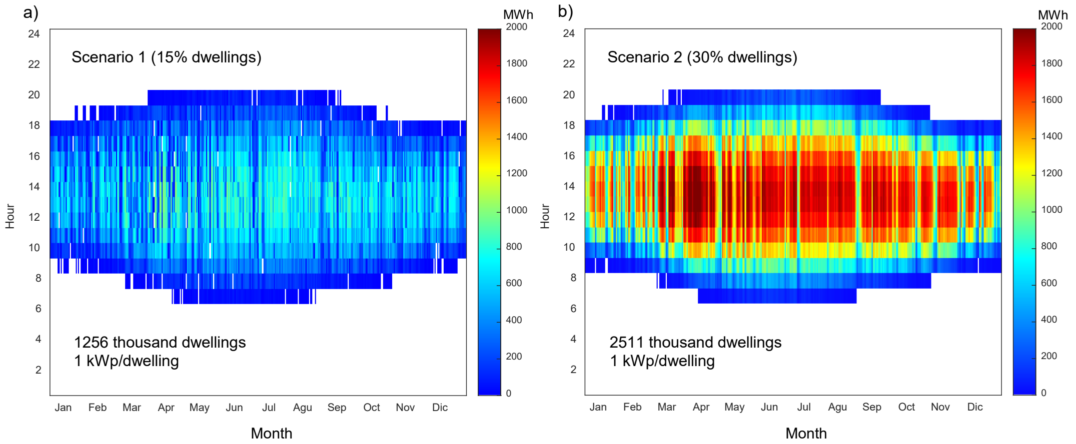

Figure 7. Values of nationwide aggregate PV self-production for each hour of 2017 for a) Scenario 1 and b) Scenario 2.

The colour maps of Figure 8 show the hourly variations of the traded energy, $\Delta W_h(\Delta E_{sc\text{-}h})$, and clearing price, $\Delta p_h(\Delta E_{sc\text{-}h})$, for each of the 8760 hours of the considered year, corresponding to scenarios 1 and 2, where both daily and seasonal variations can be observed.

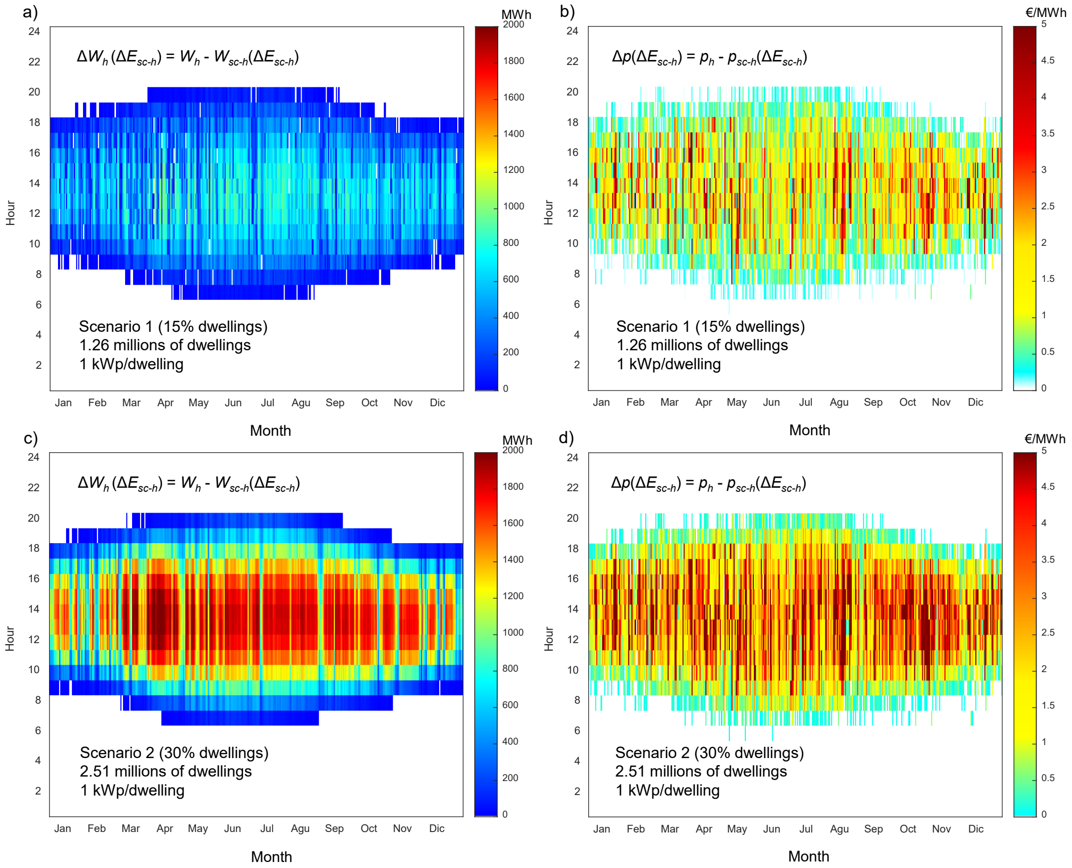

Figure 8. Values of the reductions of trade energy (left) and clearing prices (right) resulting from PV self-consumption for each hour of 2017 for scenarios 1 (up) and 2 (bottom).

Table 1 summarizes the annual variations of the traded energy, ΔW, the average hourly clearing price, Δp and the annual cost of the traded energy, ΔC, for the different scenarios of demand reduction, ΔE_{SC}, derived from self-consumption.

Table 1. Variations of the annual traded energy, the mean hourly clearing price and the annual cost of the traded energy in the market. Effect on the day-ahead market of the reduction of the demand for PV self-consumption.

OMIE Day-ahead Market 2017	**Unit**	**Scenario 1 15% dwellings, 1 kW/dwelling ΔE_{SC} = 2267 GWh**	**Scenario 2 30% dwellings, 1 kW/dwelling ΔE_{SC} = 4535 GWh**
$\Delta W(\Delta E_{sc}) = \sum_h \left(W_h - W_{sc-h}(\Delta E_{sc-h})\right)$	GWh	-1697	-3264
$\Delta p_{av}(\Delta E_{sc}) = \frac{1}{8760}\sum_h \left(p_h - p_{sc-h}(\Delta E_{sc-h})\right)$	€/MWh	-0.58	-1.16
$\Delta C(\Delta E_{sc}) = \sum_h \left(C_h - C_{sc-h}(\Delta E_{sc-h})\right)$	M€	-241	-470
$\Delta W(\Delta E_{sc}) / \Delta E_{sc}$	-	-0.75	-0.72
$\Delta C(\Delta E_{sc}) / (\Delta E_{sc} \cdot N_{sun\ hours})$	€/MWh^2	-0.029	-0.028
$\Delta C(\Delta E_{sc}) / \Delta E_{sc}$	M€/GWh	-0.106	-0.104

Base case 2017	Annual traded energy $W_B = 243$ TWh*	Mean hourly price $p_B = 52.24$ €/MWh	Annual cost of the traded energy $C_B = 13035$ M€

*Spain: $W_{SP} = 192$ TWh (79.2%); Portugal: $W_{PT} = 51$ TWh (20.8%)

The penetration of residential PV systems leads to the following main effects on the market:

- The mean values of the annual traded energy, ΔW, the clearing price, Δp and the annual cost of the traded energy, ΔC, underwent a clear decrease. These reduction results were almost proportional to the amount of energy, ΔE_{SC}, produced by the considered residential PV self-consumption systems.
- The reduction of the traded energy in the market was lower than the total amount of energy bids removed from the demand ($\Delta W(\Delta E_{SC}) < \Delta E_{SC}$). A reduction of one MWh in demand bids due to PV self-consumption yielded a diminution of around 0.73 MWh (0.72-0.75 MWh) of traded energy, because some consumers are encouraged to buy more electricity at a lower price.
- For Scenario 1, the annual mean clearing price was reduced by about 0.58 €/MWh, which means a 1.11% reduction of the price of the base case. Thus, a curtailment of the demand equivalent to 1% of the annual demand due to PV self-consumption led to a reduction of the annual mean clearing price of 1.19%.
- For the base case, the annual cost of the traded energy was C_B =13035 M€, approximately. For Scenario 2, the savings produced by self-consumers were about 470 M€ (3.61% of the base case). Accordingly, a curtailment of the demand equivalent to 1% of the annual demand due to PV self-consumption lead to a reduction of almost 2% of the annual cost of the traded energy. The annual cost of the traded energy was reduced by around 0.104 M€ per GWh of the annual energy produced by the residential PV systems.
    - For Scenario 2, and based on the results of (Roldán et al., 2021), the annual savings in the electricity bill for an average domestic consumers (2.0 A tariff) who installed PV self-consumption systems reached about 494 M€, a value that was even higher than the savings in the market.

4.2 Discussion

The reduction of the demand in the wholesale market derived from self-consumption left-shifted the aggregated demand curve, leading to a reduction of the clearing price, traded energy and the cost of traded energy. Therefore, the amount of energy no longer required, the more expensive generation bids, those that in the base case were the last generation (marginal) units being dispatched by the market operator, were no longer cleared. Accordingly, the more expensive generators experienced an income decrease. Simultaneously, some consumers' bids, those with a price just under the initial clearing price but over or equal to the lower new market price, were now dispatched by the market operator, benefiting from lower prices.

There are other interesting side effects derived from PV self-consumption that should be considered, even briefly, such as the following. Since self-consumption scenarios require less generation and distribution of energy, a reduction of the electrical losses in the transmission and distribution system can be expected. Since the system is less loaded, less technical restrictions are expected and the investments for reinforcement or new infrastructure (generation capacity, lines transformers, etc.) could be delayed. A reduction in CO_2 emissions is also expected. This reduction is produced in two ways: less energy is necessary from the grid (which leads to an additional reduction of the system losses) and this production is achieved without the participation of some thermal units (coal and combined cycle). The Spanish energy dependency rate is also expected to diminish (improvement of the balance of payments) as a consequence of PV self-consumption. This effect would be especially interesting for a country which depends on imported energy resources such as Spain, whose energy dependency rate was about 74% in 2017.

It is also worth observing how a joint wholesale market, such as OMIE, causes the economic effects of self-consumption to spread geographically, even crossing national borders, as was already shown by Roldan-Fernandez et al. (2018b). In this work, despite the fact that, in the considered scenarios, the policy of promoting self-consumption and the installation of individual PV systems were considered a Spanish initiative, all consumers in the joint Iberian market, both Spanish and Portuguese, would enjoy lower electricity prices and reduced energy costs. In the same way, all the generators of the system would experience an income reduction. For example, in Scenario 2 and with the annual traded energies in the Spanish and Portuguese systems taken into account, of the 470 M€ saved by Iberian consumers, Portuguese consumers saved 98 M€ (372 M€ for Spanish consumers), although the installation of individual PV self-consumption systems was considered a Spanish initiative. This is a remarkable cross-border geographic propagation of the effects of national policies, in which the plans promoted by one country and executed by some of the consumers in that country have measurable economic effects on the consumers and generators of other neighbouring countries.

Finally, the estimate made on income flows may allow policymakers to consider bosting PV self-consumption promotion through subsidies, as long as it does not entail an excessive overburden on any of the agents.

5. Conclusions

This work provides an estimate of the potential economic impact of foreseeable scenarios of self-consumption on the day-ahead Iberian/Spanish Electricity Market, using a ceteris paribus approach. The analysis showed that the development of individual PV self-consumption in Spain will lead to a reduction of the demand, which would modify the hourly merit-order demand curve in the market, leading to a reduction of both the traded energy and the clearing price. In this work, the demand curtailment was estimated by taking into account the actual number of dwellings in Spain and assuming that a proportion of them are willing to install a small 1 kWp PV system. The Spanish nationwide PV self-consumption production was estimated using actual production data from existing PV plants spread across the country. For each hour of 2017, the day-ahead Iberian Electricity Market was reproduced, with consideration of the appropriate demand reduction and recalculation of the new clearing price and traded energy. The main results obtained showed that:

- The ratio between the reduction in the traded energy and the amount of energy removed, $\left|\Delta W(\Delta E_{sc})/\Delta E_{sc}\right|$, ranged between 72-75% for the considered scenarios.

    - The downward pressure on the market prices encouraged some customers to acquire more energy at a lower price than in the base case.
- Despite the fact that the traded energy is reduced less than the energy withdrawn by self-consumption, 1% of the annual demand for photovoltaic self-consumption leads to a reduction of almost 2% in the annual cost of the traded energy. Each GWh of annual energy removed from the demand due to PV self-consumption will lead to a reduction of about 0.104 M€ in the annual cost of the traded energy in the market.
    - The reduction in the electricity bill reached 0.118 M€/GWh for domestic consumers (2.0 A tariff) who installed PV self-consumption systems.
- Overall, consumers will take advantage of lower prices in electricity, reducing the total cost of the traded energy.
- Expensive generators experience a decrease in their income, since part of their production is no longer required in the new self-consumption scenarios.

It is worth mentioning that, despite the fact that, in the considered scenarios, the policy of promoting self-consumption and the installation of individual PV systems were considered a Spanish initiative, all consumers in the joint Iberian market, both Spanish and Portuguese, would enjoy lower electricity prices.

To conclude, the promotion PV self-consumption, apart from the impact on the market analysed in this work, is expected to contribute to reduction CO_2 emission and energy losses in the electricity system, but also to the reduction of the Spanish fuel import dependence and to the improvement of the Spanish balance of international payments. Some of these points will be soon addressed by the authors in future works.

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