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Assessing the decarbonisation effect of household photovoltaic self-consumption

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ABSTRACT

the combination of falling renewable technology costs, with high and rising electricity prices and non-obstructive national regulations are making distributed generation increasingly attractive. In the case of photovoltaic (PV) systems, even domestic consumers find it profitable to self-produce part of their electricity demand, instead of purchasing all their energy from the grid, which is changing the current way of obtaining and consuming electricity. The purpose of this work is to estimate the decarbonisation effect in the Iberian/Spanish market, produced by domestic PV self-consumption, once the new regulation, passed in 2019, has removed the previous regulatory barriers in Spain. To achieve this goal, the nationwide, distributed, domestic PV self-production was turned into a reduction of the aggregate demand in the market, and the new clearing point and the corresponding dispatched generators list was established, by emulating the performance of the market operator. Based on 2016–2019 market data, the results suggest that self-consumption could decarbonise the Iberian electricity market, with an average rate of just over 300 $tCO_{2\text{-eq}}$/year for each GWh/year of household PV self-consumed energy.

1. Introduction

Over the past few decades, various energy and supply crises, along with the growing emphasis on mitigating anthropogenic climate change, have contributed to a remarkable and sustained development of renewable energy. More recently, the deployment of a multitude of small renewable domestic installations, at LV level, have been added to this general trend. This is particularly true in the case solar PV technologies, the costs of which are decreasing rapidly and sustainably. From 2010 to 2019, global weighted, average, total, installed PV costs decreased by around 79% (IRENA, 2019). In addition, as can be seen in Fig. 1, electricity prices in Spain for residential consumers (2.0A PVPC tariff) have experienced a gradual growth during this time, making home PV systems increasingly more attractive. Consequently, new actors, such as prosumers (producers/consumers), are already beginning to play an important and increasingly relevant role in this new CO_2-free energy paradigm. Future scenarios of residential PV generation can change the current consumption time-profile, since the nationwide aggregated residential PV self-produced and self-consumed energy will lead to a reduction in the total domestic demand, withdrawn from the grid/system during daylight hours. Since it is no longer necessary for the system to provide household PV self-produced energy, the market operator will be forced to remove/reject the production of certain generators, which previously were the last cleared/dispatched generation units (marginal). The fact that PV energy is utilized at the consumers' homes, the last point/node in the energy transmission and distribution network, brings other indirect benefits, such as a reduction in transmission losses or the congestion risk at peak daylight hours. EU countries and others, aware of the benefits of renewable self-consumption, have promoted policies that help their development.

According to the European Association of Solar Power, at least 600 GW of rooftop capacity remains untapped across the EU (Solar Power Europe, 2019). Countries such as Portugal, Spain, parts of southern France, Italy and Greece enjoy an optimal location for the development of residential solar PV energy, with a PV annual energy potential greater than 1.3 MWh/kWp (Solargis, 2019), as shown in Fig. 2. This figure also shows the projected residential PV capacity by 2030 (Prosumers, 2017). This 2017 forecast, prior to the regulatory change in Spain, shows the anomalous situation of self-consumption in Spain with the previous regulation currently repealed.

Despite the abundance of solar resources in Spain, this figure illustrates that the installed solar rooftop power is particularly scarce. This

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paradoxical situation is motivated by previous 2018–2019 legislation that made domestic solar energy investments very unattractive. Nevertheless, since 2019, a new regulation has been passed, responding to this new paradigm. The Royal Decree 244/2019 (RD, 2019) completes the regulatory framework for self-consumption, promoted by Royal Decree-Law 15/2018 (RDL, 2018), developing the administrative, technical and economic conditions of consumers' self-consumption. This work seeks to evaluate the reduction of $CO_{2\text{-eq}}$ emissions in the electricity production system when a significant element of the demand is satisfied by distributed domestic PV self-consumption.

Previous research works have mainly focused on the viability of solar PV rooftop residential projects, in relation to the previous (Steininger, 2017; Camilo et al., 2017) and current regulations (Roldán-Fernández et al., 2021a). In a previous work (Roldán-Fernández et al., 2021b) we analysed the impact of domestic PV systems on price in the Iberian market. In this work, we investigate and quantify the reduction of greenhouse gas (GHG) emissions, produced by the integration of new PV self-production, which are not addressed as often in the literature relating to electricity markets, taking the Iberian market as a reference. The intensity of this decarbonisation effect depends on the amount of fossil-fired generation and the technology of the thermal power plant (coal, gas) participating in the electricity market, but also the time of the day that they access the market.

The integration of large utility-scale renewable electricity power plants, substituting fuel-fired production units as a means of reducing the $CO_{2\text{-eq}}$ emissions of the market, has been widely addressed and analysed in the literature. Another similar problem, also broadly studied for the research community, has been the evaluation of greenhouse gases (GHG) emissions, due to the participation of fuel-fired thermal plants in markets with a known fleet or structure of generation technologies. Wang et al. (2019) studied the contribution of non-fossil fuel power generation to $CO_{2\text{-eq}}$ emission reduction from the electricity sector across 30 provinces in China over the period 1991–2015. They found that a 1% increase of non-fossil fuel power generation share reduce electricity-related $CO_{2\text{-eq}}$ emissions by over 2%. To and Lee (2017) analysed the fuel mix and GHG emissions from electricity consumption in Hong Kong. Their results have shown that, during the period 2002–2015, coal had contributed 74.3%, on average, to the generation of electricity. They stated that cities with rapid economic growth have to pay strategic attention and apply resources to alleviate their GHG emissions. They concluded that increasing the use of liquefied natural gas in the generation of electricity is an effective means of reducing GHG emissions resulting from electricity consumption. The effects of a German coal phase-out policy on carbon emissions, by comparison with the effects of EU-wide coal phase-out policies, were analysed by Keles and Yilmaz (2020). They stated that considering high CO_2 certificate prices and ambitious renewable energy targets, a coal phase-out in Germany would have a minor additional impact on overall European emissions. However, they also found that an EU-wide coal phase-out would reduce emissions, by around 19%. Kraan et al. (2019) evaluated the cases of an "energy-only" market and a market with a capacity remuneration mechanism, in order to assess the possibility of a transition towards a decarbonisation of the electricity system, concluding energy-only markets, even with strong carbon pricing, do not encourage investors to deliver a fully renewable, reliable and affordable energy system. Figueiredo et al. (2019) analysed the phase-out of the two remaining coal-fired power plants in Portugal. Using data of 2015 they found, among other things that coal plants with a total capacity of 1.7 GW and an annual production of 13.74 TWh (28% of the Portuguese generation mix) could be replaced by about 8 GW of PV if accompanied by a modest increase in the already existing hydro pump capacity. The PV scenario would reduce a 51% the volume of CO2-eq emissions.

Other works addressed the integration of a PV installation in buildings which adds extra functionalities to houses. PV energy can be installed in a building using two techniques: building integration (BIPV) and building attached or applied (BAPV). For new buildings, BIPV can replace conventional construction material and harness aesthetically, benign electricity from PV. In the case of homes already built, BAPV does not replace structural components, although by shading a roof or wall from direct solar heat, this helps reduce the heat gain of the building. A recent work by Ghosh (2020) shows a comprehensive review of the potential of BIPV/BAPV for buildings with a lower energy consumption skin. Researchers have also addressed the problem of carbon-dioxide mitigation in commercial and residential building sectors in China. Ma, Cai, and Cai (2018) introduced a bottom-up model for measuring the carbon abatement in China's commercial buildings (CACCB) based on decomposing the extended Kaya identity via the Logarithmic Mean Divisia Index method. Their results indicate, among other things, that the more significant CACCB effects observed in recent years (2000–2015) can be attributed to the significant improvements made in energy conservation work. Ma et al. (2019) investigate the factors that can mitigate CO_2 intensity and further assess carbon-dioxide mitigation in residential building sector (CMRBS) in China based on a household scale via decomposition analysis. They found, among other things, that energy-conservation effectively caused CMRBS and that will be the key to promoting more significant emission mitigation in the future. Ma et al. (2020) assessed the historical carbon mitigation and simulated the energy and emission peaks of China's residential building sector using a dynamic emission scenario. Their results suggested that the emission mitigation of the residential building sector during 2000–2015 was 1.817 (±0.643) billion tons of carbon dioxide ($BtCO_2$), and that the residential building sector will achieve a carbon emission peak of 1.419 (±0.081) $BtCO_2$ in 2037 (±4).

The research community has also addressed the problem from the point of view of mitigation costs. Santos-Alamillos et al. (2017) evaluated the costs of a gradual transition towards a new power system, taking as a case study, the PJM Interconnection, one of the power systems in the United States with the largest fraction of coal. They concluded that the most environmentally responsible pathway to replace retiring coal-fired power plants in PJM is to add new wind farms at the windiest locations, accompanied by better management of

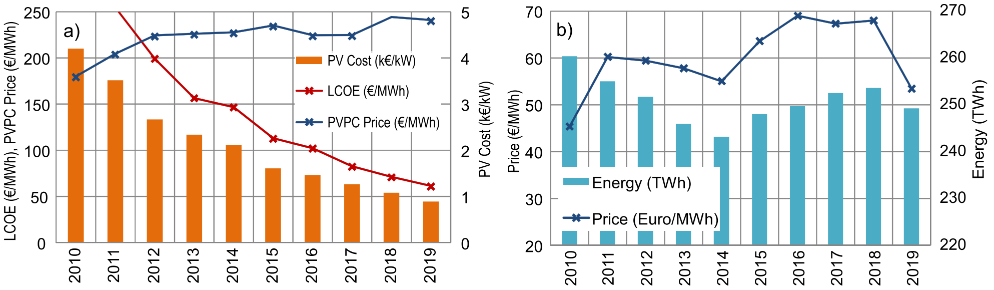


Fig. 1. 2010–2019 Evolution of a) the global weighted average total installed PV costs and PV LCOE, as well as the low voltage tariff price (PVPC price), b) the yearly average price and traded energy in the Iberian/Spanish market.

existing plants and a small addition of new natural-gas reserve capacity. Vellini et al. (2020) considered the Italian case to quantify the economic burden associated with the reduction of direct CO_2 emissions. They compiled a ranking of various alternatives, proposed for the Italian authorities for the year 2030, according to their mitigation costs. The authors included a note on energy efficiency, adding that to achieve a high environmental performance, energy consumption must be reduced.

Other works focus on aspects related to the effects of temporal and geographical profiles. For example, Khan (2018) applied a time-varying carbon intensity approach to assess the GHG emissions of an electricity system, dominated by fossil fuel generation, when studying the case of Bangladesh. The paper assessed three main factors: (a) appropriateness of demand-side management application; (b) renewable integration opportunities and (c) the impact of power plant efficiencies. Khan concluded that the time-varying carbon intensity analysis reveals a number of significant policy implications for reducing GHG emissions of the country's electricity sector emissions. Olkkonen and Syri (2016) studied how spatial and temporal variations, related to a particular energy system, may affect a marginal generation unit. They characterized short-term (2009–2010) and long-term (until 2030) hourly marginal generation units and marginal emission intensities, using the Finnish, Nordic and European energy systems as actual cases. They found that marginal generation technology and marginal emission intensities differed significantly within the studied time horizon and between the studied countries and energy systems.

The aim of this work departs to a certain extent from mainstream studies, since it does not focus on substituting fuel-fired generators, with alternatives based on renewables. In fact, our work does not consider any change in the generation fleet of the market or power system. As has been shown in the literature review, the way in which the emergence of domestic self-consumption in a country such as Spain can alter the Market Operator's dispatching decisions and, consequently, the hourly lists of units dispatched in the market and the associated greenhouse gases GHG emissions, As has been shown in the literature review, the way in which the emergence of domestic self-consumption in a country such as Spain can alter the market operator's dispatching decisions and, consequently, the hourly lists of units dispatched in the market and the associated GHG emissions, is an issue that has been little addressed by the research community until now. In this work, we present the analysis of how a measure at the domestic consumer level, such as the prosumer activity through PV self-consumption, can affect the GHG emissions of generators, dispatched by market operators. In other words, this research aims to estimate how PV self-consumption, at the level of domestic consumers, is capable of modifying GHG emissions through changes induced in the hourly dispatched generators list. To reach that goal and based on the hourly data (35064 market hourly time slots) of the 2016–2019 Iberian market, once the distributed domestic PV self-produced energy is aggregated at country level, it is transferred to the market as a reduction in demand, since it is no longer necessary to purchase the amount of self-consumed energy from the grid. This reduction in demand leads to a modification of the aggregate demand curves in the market. Subsequently, a new clearing point is obtained, leading to a new list of generation units and share of technologies involved in the PV self-consumption scenario. The identification of fuel-fired units and the amount of energy dispatched hourly in the PV self-consumption scenarios allows a detailed evaluation of the amount of $CO_{2\text{-eq}}$ emissions.

After this introduction, the Iberian/Spanish electricity market and the new self-consumption regulation are surveyed in Section 2. The main sources of information and the methodology, used in this work, are presented in Section 3. Then, the details of the considered household PV self-consumption scenarios and their impact in the market are presented in Section 4. That section closes with a discussion of the results and the meaning of the decarbonisation effects. Finally, the main conclusions of this work are summarized.

2. Background: household self-consumption and electricity market

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*

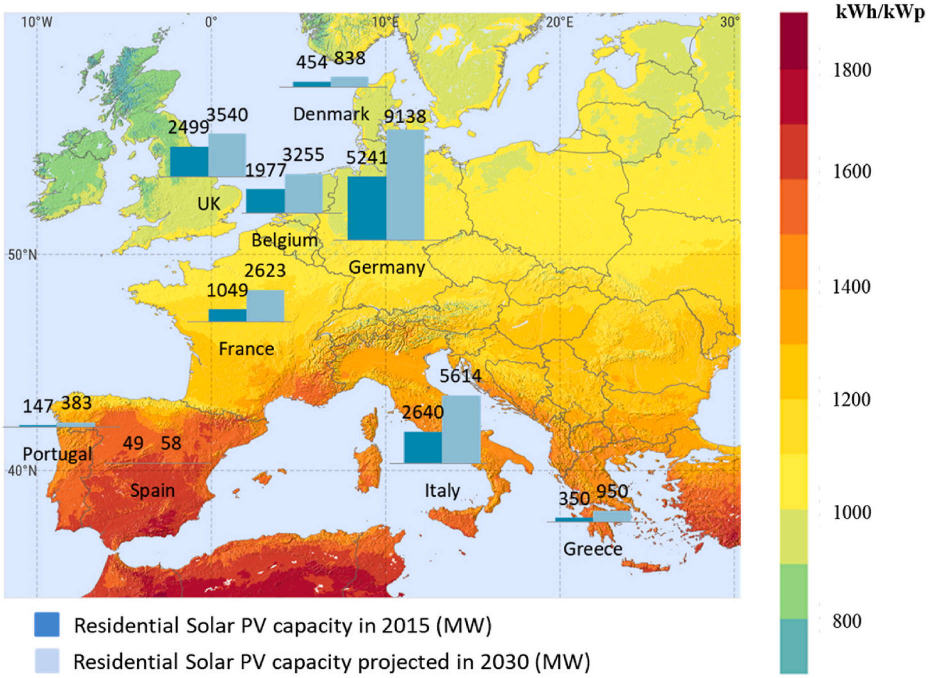


Fig. 2. PV annual electricity potential (kWh/kWp) and residential solar PV capacity 2015 and projected capacity (before the regulatory change in Spain) for 2030 (MW).

regulatory framework which would empower renewables self-consumers to generate, consume, store and sell electricity without facing disproportionate burdens.

The Spanish regulation, according to the EU Directive, considers both renewables self-consumers and jointly acting renewables self-consumers or collective self-consumption.

To analyse and evaluate the decarbonisation effects on the generation derived from the development of domestic renewable self-consumption in Spain, it is convenient to survey the Iberian electricity market, and how the new self-consumption regulation and the prosumers activity is linked with the wholesale market operation.

2.1. The Iberian electricity market

OMIE is the market operator of the Iberian market, that is, the joint European regional market for Portugal and Spain. The Iberian market is only connected with the central European system through the French-Spanish border. The current **interconnection ratio of Spain is 2.8%, well below the minimum target of 10%, recommended by the EU for 2020. Accordingly, the Iberian system can practically be considered an electrical island.**

The purpose of the day-ahead market is to determine the electricity transactions for the following day. The day-ahead electricity market determines to a large extent the electricity prices in both countries, since the daily market arranges around 80% of the electricity, jointly produced in Spain and Portugal. The wholesale market is organized as a sequence of markets: the daily market, the intraday markets (six sessions a day and a continuous European cross-border market) and the ancillary services markets. The day-ahead market consists of 24-hourly markets or auctions which clear once a day, determining the amounts of traded energy and the clearing prices for each of the 24 h of the following day. The clearing point also sets the list of dispatched generators. To determine the energy transactions for the following day, the market operator orders bids submitted from generation (sellers) and demand (purchasers/buyers) agents, one day ahead of these physical transactions taking place (OMIE, 2021a).

Demand agents elaborate their purchase bids by establishing the amount of energy they wish to purchase and the maximum price at which they are willing to buy that energy. These are called single bids. Generation units are also allowed to submit supply bids with complex conditions, that is, bids with additional restrictions such as the indivisibility of blocks of energy, minimum income, scheduled stops and the load gradient (OMIE, 2021a).

2.2. The Spanish power system

Fig. 3 a) shows the evolution of the structure of installed power capacity on the Spanish peninsular system since 2010 (REE, 2020a). As shown, the structure of the electricity generating facilities is increasingly renewable and less dependent on fuel-fired technologies which, in the case of Spain, are purchased abroad, causing the Spanish energy dependence rate to be higher than the European average. Among renewables, it is noteworthy that the solar PV installed capacity grew from 4.46 GW in 2018 to 8.67 GW in 2019.

Fig. 3 b) shows the evolution of the percentage of renewable and non-renewable electricity generation on the Spanish peninsular system since 2010 (REE, 2020a). The share of renewables in the generation mix varies from a year to other, mainly due to variations in the rainfall regime. Nevertheless, the renewable average quota of the last decade reached 37.3%. In order to mitigate the possible effect of years of

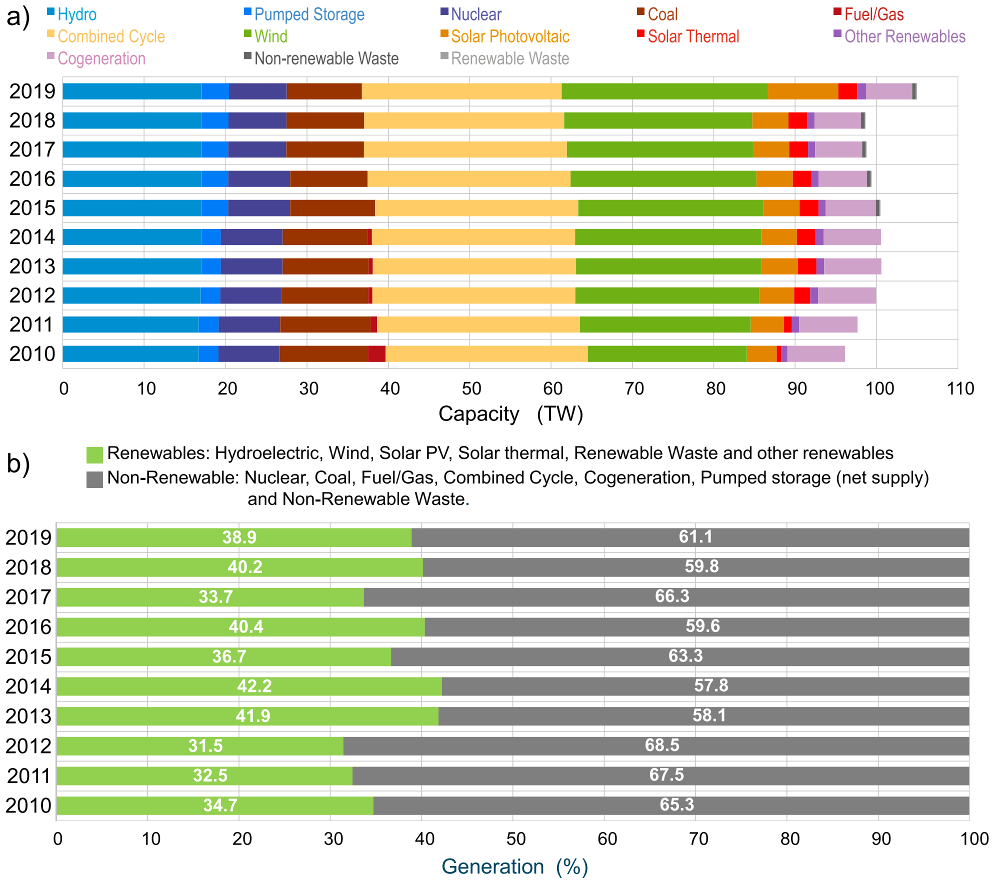


Fig. 3. Evolution of the Spanish peninsular system 2010–2019: a) breakdown of the installed power capacity and b) renewable and non-renewable electricity generation.

different rainfall regimes on the generation mix, the four-year period, 2016–2019, has been studied.

3. Materials and methods

Since household self-produced energy is no longer withdrawn from the grid, the aggregation of distributed self-consumption at country level becomes a demand reduction at the electricity market level. As a result of this demand reduction, the production of certain conventional generators (some of them fuel-fired) is no longer necessary. Thus, household self-consumption leads to a demand contraction in the market and to a reduction in CO2-eq emissions.

Accordingly, the basic information to evaluate the decarbonisation effect of the household PV prosumers is mainly the hourly demand profile of an average dwelling, the hourly household PV production of an average dwelling in Spain and the full hourly dataset of market data, including the technology of the dispatched generators. The hourly demand profile of an average dwelling has been retrieved from the archive of REE, the system operator (REE, 2021). The hourly household PV self-production profile has been elaborated using the interactive tool, Photovoltaic Geographical Information System (PVGIS, 2020) and considering average conditions for Spain, that is, a dwelling located in the centre of the country (near Madrid). Finally, the background information for the market has been the full hourly dataset, corresponding to the four-year period from 2016 to 2019, retrieved from the market operator (OMIE, 2021b).

After the hourly household PV self-production profile of an average dwelling is elaborated, the profile is extrapolated to the country or market level, according to the number of dwellings with PV facilities considered in each self-consumption/prosumer scenario. That amount of energy is no longer withdrawn from the LV grid or from the market. Accordingly, distributed energy, self-produced, turns into an aggregated demand reduction in the market. Once the hourly aggregated demand curve has been curtailed, the new hourly market clearing points are calculated, setting the list of dispatched generators. The knowledge of the dispatched generator technology allows the evaluation of the hourly amount of CO2-eq emissions, which finally determines the decarbonisation effect of every household PV self-production scenario (Fig. 4).

3.1. Electricity market and household PV self-consumption

In this work, three different scenarios of PV self-consumption penetration have been considered, each of them based on Iberian market data for the period 2016–2019. Since these are rather long-term scenarios, a simplified method was used to reproduce the 3x1461 = 3383 daily market sessions. Several different approaches have been considered in previous research relating to the daily market. A simplified model, based on the linearization of the market around the clearing point, was utilized in Burgos-Payan et al. (2013), Roldan-Fernandez et al. (2016a, 2016b) and Märkle-Huß et al. (2018). Research based on a market model, using generation and demand curves, can be found in Ciarreta et al. (2014) and Roldán-Fernández et al. (2016c, 2017, 2018). The latter methodology has been adopted in this work, which requires very detailed information regarding the composition of generation and demand curves, especially in terms of identifying the technology and the amount of energy of each generator, dispatched hourly by the market operator. The hourly merit-order generation and demand curves, corresponding to the period 2016–2019 (OMIE, 2021b), form the basis of the self-consumption scenarios.

Fig. 5 a) shows the generation and demand curves elaborated by the market operator for a specific hour. As can be seen, the market operator creates simple generation and demand stepped curves, by sorting the demand and supply bids by price; in ascending order for generation bids and in descending order for demand bids.

Once the complex conditions of the generation bids have been included, the Iberian market operator has to clear the market by means of EUPHEMIA, the overall social welfare (surplus of producers and consumers) optimization Pan-European algorithm (NEMOs, 2019). As a result, the market clearing point (A in Fig. 5 a)) are obtained, as well as the dispatched generation and demand curves. This point not only sets the amount of energy that is going to be traded for that hour and the price of the transaction, but also determines the particular generation units dispatched to produce and sell the energy, as well as the demand agents who will purchase that energy.

To ensure their bids are cleared by the Iberian market operator, the market agents of domestic consumers send demand bids with a maximum price of 180.3 €/MWh. Accordingly, these bids are placed on the initial flat section of the actual cleared demand curve of Fig. 5 a). In a household self-consumption scenario, energy bids, corresponding to

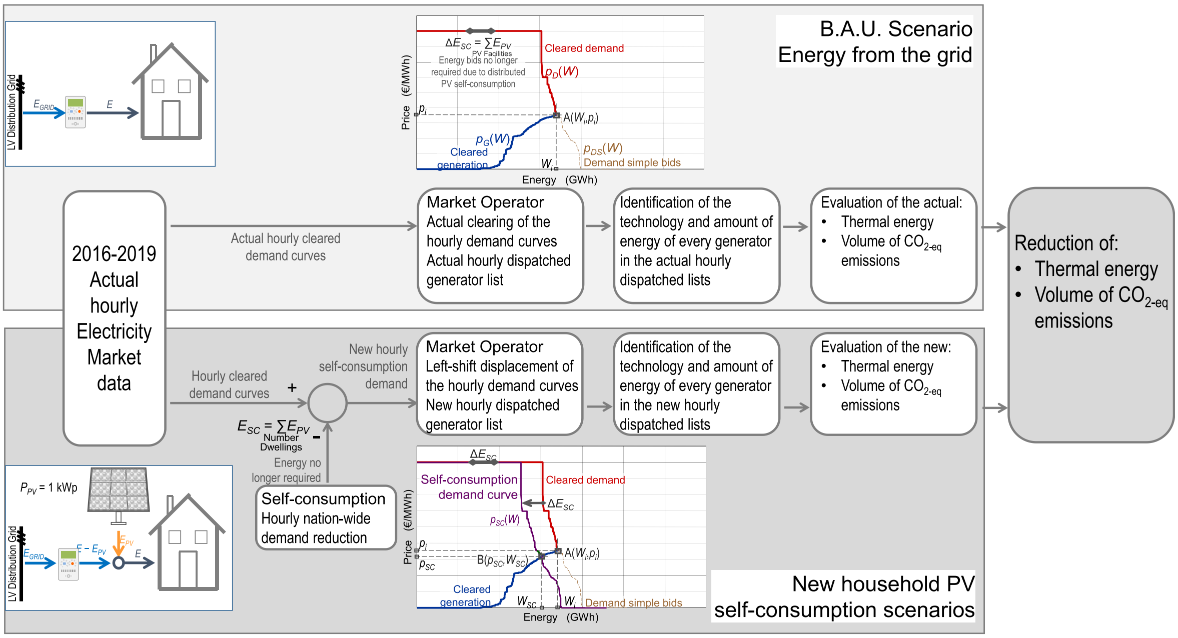


Fig. 4. A simplified diagram of the proposed methodology to evaluate the decarbonisation effect on the market of the household PV self-consumption.

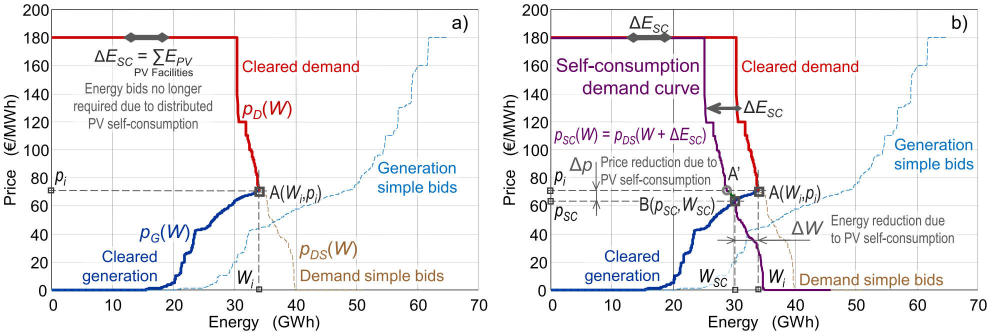


Fig. 5. Example of 1-h data from day-ahead electricity market: a) actual generation and demand curves retrieved form OMIE and b) elaboration of the self-consumption reduced demand curve and determination of the corresponding new clearing point.

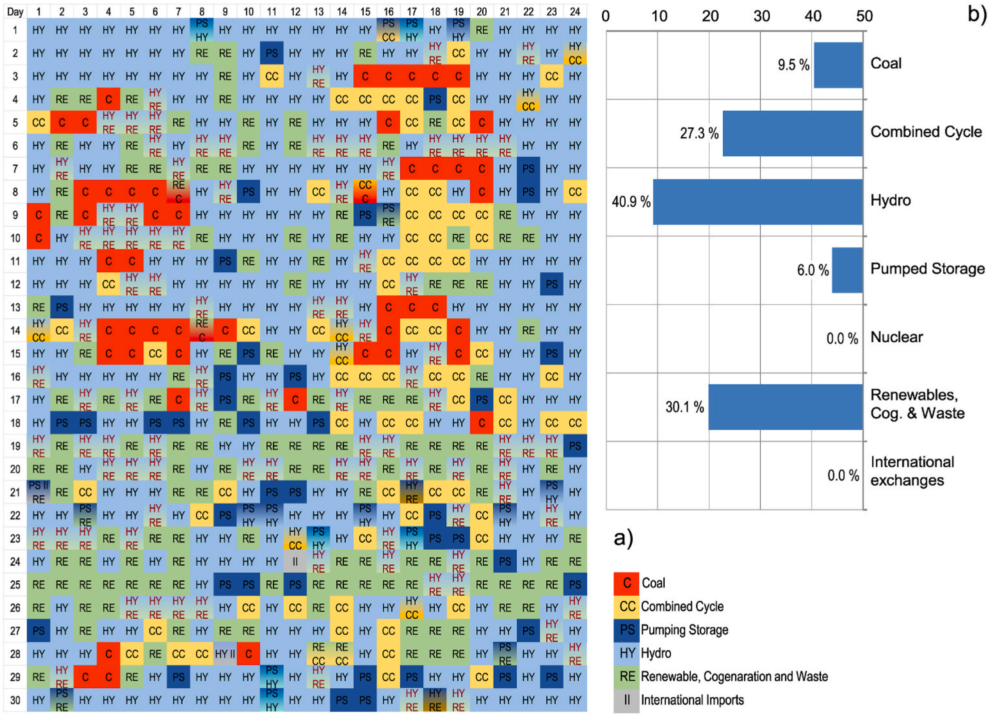
domestic consumer agents, that will no longer be necessary due to household self-consumption, can be found on the initial flat section of the aggregate demand curve. Although these bids will actually be distributed throughout the initial flat section of the demand curve, for simplicity, in Fig. 5 b), it has been considered that they will all join together.

Accordingly, using the actual 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 aggregation of the PV generation of the considered self-consumption scenario ($\Delta E_{SC\ h} = \sum E_{PV\ h}$). Since the simple demand bid curve includes the demand cleared curve, ($p_D(W) = p_{DS}(W)\ \forall\ W \leq W_i$) and covers the full range of prices or energies, the new demand curve, corresponding to the self-consumption scenario, has been developed based on the simple bid curve, $p_{SC}(W) = p_{DS}(W + \Delta E_{SC})$, as shown in Fig. 5 b). The new clearing point (B in Fig. 5 b)) is then obtained as the intersection of the new left-shifted demand curve, with the originally cleared generation curve.

This procedure is used for each of the 1,461 day-ahead markets (35,064-h time slots) from 1st January 2016 to 31st December 2019, obtaining the new hourly clearing prices and traded energy for each of the considered PV self-consumption scenarios, as well as the hourly lists of generators dispatched.

As can be observed, PV self-consumption leads to a kind of *merit-order effect* in the wholesale market, which is similar to the well-known merit-order effect of renewables (right-shifting of the generation curve) in that it reduces the clearing price and the cost of the traded energy in the market, although it differs from renewables in which self-consumption reduces the amount of traded energy in the market (Roldán-Fernández et al., 2016a). Since self-produced energy at home is no longer necessary to be purchased in the market, generators with bids placed between the initial and final clearing points (A and B in Fig. 5 b)), are not dispatched by the market operator, as their bids are more expensive than the new clearing price. These generators will be called inter-marginal units and will play an essential role in the decarbonisation effect of self-consumption, as will be shown.

The integration of renewables in the market leads to a similar effect of substitution of some of the conventional generators, the production of which, now overpriced, is no longer necessary and as a result is replaced by renewable generators. In both cases, the clearing price reduction also encourages certain demand agents to acquire more energy (rebound



Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	HY	HY	HY	HY	HY	HY	HY	PS HY	HY	HY	HY	HY	HY	HY	HY	PS CC	PS HY	HY	PS HY	RE	HY	HY	HY	HY
2	HY	HY	HY	HY	HY	HY	HY	RE	RE	HY	PS	HY	HY	HY	RE	HY	HY	HY RE	CC	HY	HY	HY RE	HY	HY CC
3	HY	HY	HY	HY	HY	HY	HY	HY	RE	HY	CC	HY	HY RE	HY	C	C	C	C	C	HY	HY	HY	CC	HY
4	HY	RE	RE	C	RE	HY RE	HY	HY	RE	HY	HY	HY	HY	CC	CC	CC	CC	PS	CC	HY	HY	HY CC	HY	HY
5	CC	C	C	HY RE	HY RE	HY RE	RE	HY	HY	RE	HY	RE	HY	HY	HY	C	CC	RE	CC	C	HY	HY	HY	HY
6	HY	RE	HY	HY	RE	HY RE	HY	HY RE	HY RE	RE	HY	RE	HY RE	HY RE	HY RE	RE	HY	HY RE	HY RE	HY RE	HY RE	HY	HY	HY
7	HY	HY RE	HY	HY	RE	RE	HY RE	RE	RE	HY	HY	HY	HY	HY	HY	HY RE	C	C	C	C	HY	PS	HY	HY
8	HY	RE	C	C	C	C	RE C	HY	HY RE	PS	HY	HY	CC	HY RE	CC C	HY	CC	CC	HY	C	HY	PS	HY	CC
9	C	RE	C	HY RE	HY RE	C	C	HY	HY	HY	HY	HY	HY	RE	PS	PS RE	CC	CC	CC	CC	RE	HY	HY	HY
10	C	HY	HY RE	HY RE	HY RE	HY RE	HY RE	RE	HY	HY	HY	RE	HY	RE	HY	HY	CC	CC	RE	CC	RE	RE	HY	HY
11	HY	HY	HY	C	C	HY	HY	HY	PS	RE	HY	HY	RE	HY	HY RE	CC	CC	CC	CC	HY	HY	HY	HY	HY
12	HY	HY	HY	CC	HY RE	HY RE	HY	HY	HY	HY	HY	RE	HY	HY	HY	CC	HY RE	RE	RE	RE	HY	HY	PS	HY
13	RE	PS	HY	HY	HY	HY	HY	HY RE	HY	HY	HY	HY	HY RE	HY RE	HY	C	C	C	HY	HY	HY	HY	HY	HY
14	HY CC	CC	HY RE	C	C	C	C	RE C	C	CC	HY	HY	CC	HY CC	HY RE	C	CC	CC	C	HY	HY	RE	HY	HY
15	HY	HY	RE	C	C	CC	C	HY	RE	PS	RE	HY	HY	HY CC	C	C	HY	HY RE	C	CC	HY	HY	PS	HY
16	HY RE	HY	HY	HY	HY	HY	RE	HY RE	PS	HY	HY	PS	HY	CC	CC	CC	HY RE	CC	CC	RE	HY	HY	CC	HY
17	HY	RE	HY RE	RE	HY RE	RE	C	HY RE	PS	RE	HY RE	C	RE	HY RE	RE	RE	RE	HY RE	CC	PS	CC	HY	HY	HY
18	HY	PS	PS	HY	HY	PS	PS	HY	RE	PS	HY	HY	PS	CC	HY	CC	CC	HY	HY	C	CC	HY	CC	CC
19	HY RE	RE	HY RE	HY RE	RE	HY RE	RE	RE	HY	HY	RE	RE	RE	RE	HY RE	HY RE	RE	RE	RE	RE	HY RE	HY RE	HY RE	PS
20	RE	RE	HY	HY RE	HY RE	HY RE	RE	HY	RE	HY RE	HY RE	RE	RE	HY RE	HY RE	RE	HY RE	RE	HY RE	RE	HY RE	HY	RE	HY
21	PS II RE	RE	CC	HY	HY	HY	RE	RE	CC	HY	PS	PS	HY	HY	RE	CC	HY RE	CC	CC	RE	HY RE	HY	PS HY	HY
22	HY	HY	PS RE	HY	HY	HY RE	HY	CC	PS	PS HY	PS HY	HY	HY	HY	PS HY	HY	CC	PS	HY RE	CC	PS HY	HY	HY RE	HY
23	HY RE	HY RE	HY RE	RE	HY RE	RE	RE	HY	HY	RE	HY	HY CC	PS HY	HY	CC	HY RE	PS HY	PS	PS	CC	HY	HY	HY	RE
24	HY	RE	RE	HY	RE	HY	RE	HY	HY	HY	HY	II	HY RE	RE	RE	HY RE	RE	RE	HY RE	RE	PS	HY	RE	RE
25	RE	RE	RE	RE	RE	RE	RE	HY	PS	PS	RE	PS	RE	RE	RE	RE	RE	HY RE	HY RE	RE	RE	RE	RE	PS
26	RE	HY	RE	RE	HY RE	HY RE	HY RE	HY RE	HY	CC	HY	CC	RE	CC	HY	HY	HY CC	HY	CC	HY	RE	RE	HY	HY RE
27	PS	HY	RE	HY	HY	CC	RE	HY	RE	RE	HY	HY	HY	CC	HY	CC	RE	RE	RE	HY	HY	PS	HY RE	HY
28	HY	HY	HY	C	CC	RE	CC	CC	HY II	C	HY	HY	RE CC	RE CC	HY	CC	RE	RE	RE	HY	PS RE	HY	HY	HY RE
29	RE	HY RE	C	C	RE	HY	PS	HY	HY	HY	PS HY	HY	HY RE	HY	PS	CC	PS	HY	HY	CC	PS	HY	PS	HY
30	HY	PS RE	HY	HY	HY	HY	HY	HY	HY	HY	PS HY	HY	HY	PS	PS	HY	HY RE	HY RE	HY RE	HY	HY	HY	HY	HY

a)

C	Coal
CC	Combined Cycle
PS	Pumping Storage
HY	Hydro
RE	Renewable, Cogenaration and Waste
II	International Imports

Fig. 6. a) Technology of the marginal units in the Iberian market in April 2019 (OMIE, 2021b), and b) percentage of hours in which generation technologies are marginal in the Iberian market in 2019.

effect). As a result, the reduction of the traded energy in the market, $\Delta W(\Delta E_{SC\ h})$, is less than the reduction of the energy bids (self-consumed energy), $\Delta E_{SC\ h} = \sum E_{PV\ h}$, that is, $\Delta W(\Delta E_{SC\ h}) = W_h - W(\Delta E_{SC\ h}) < \Delta E_{SC\ h}$.

3.1.1. Marginal units

Fig. 6 a) shows the technology of the marginal units in the Iberian market in April 2019, while Fig. 6 b) shows the percentage of hours in which each type of production technology was marginal in the Iberian market during 2019 (OMIE, 2021b). Since at certain times, there is more than one marginal technology, the sum of the technologies quota in Fig. 6 b) exceeds 100%.

As can be seen, hydro generators are often marginal units. Hydro and hydro pumped storage accounts for around half of the hours (40.6%). In fact, the exploration of the technology of dispatched generators often shows energy blocks from hydro units around the clearing unit to the left of point A in Fig. 5 a) (often there is a mix of hydro and fuel-fired units in these final positions of the dispatched generators list). However, the original marginal unit and the others before it (inter-marginal units, those placed between point A and B in Fig. 5 b)) are no longer necessary due to household self-consumption. In the case that household self-consumption rendered the production of a particular hydro unit unnecessary, the suppression of that generator within the dispatch list would not lead to a realistic market scenario. That would ignore the bidding flexibility of hydro units to adapt to new situations (unlike thermal units, hydro units use a low-cost energy). The market agents of these units will soon take note of the reduction in demand and will learn to submit bids with a slightly reduced price, which will be sufficient to continue being dispatched in the new situation.

Accordingly, in order to consider more realistic market scenarios, the methodology proposed in this work takes into account that hydro units are flexible enough to remain marginal in the new dispatch list (especially hydro-pumping generators), unlike thermal technologies which are subject to their fuel cost and to efficiency degradation when exposed to regulation. To better evaluate developments in the market exposed to household PV self-consumption scenarios and conditioned to maintaining the new clearing point (energy and price), we will proceed as follows: once the amount of energy of each technology to be removed, has been identified, the volume of inter-marginal hydro generation, found between A and B in Fig. 5 b) is re-dispatched just below (to the left side of) the new clearing point (B in Fig. 5 b)), keeping the hydro energy biding but reducing the price to the new clearing price. Therefore, the aggregated generation curve is slightly modified in the last cleared bids to re-integrate the amount of inter-marginal hydro generation in the dispatched list (the generator cannot keep the water stored indefinitely), but without any change in the new clearing point (traded energy or clearing price). The re-dispatching of inter-marginal hydro units will render unnecessary the production of certain fuel-fired generators, placed closely before the new marginal point (close to the left of point B in Fig. 5 b)).

As can be seen, as a result of the reallocation of the inter-marginal hydro generators, a lower quantity of thermal production is delivered in the new self-consumption scenario.

3.2. Household demand profile

As mentioned previously, the considered Business as Usual (BAU) or reference scenario is an average dwelling in Spain that purchases all the electricity energy from the LV grid, by means of the 2.0A PVPC tariff (Fig. 7 a)), the more common for dwellings in Spain. In 2019, according to the National Commission of Markets and Competition (BIE, 2020), the mean value of the domestic contracted power (PVPC 2.0 A tariff) was 3.73 kW and the yearly average energy demand was 2240 kWh.

Fig. 7 b) shows the clearing point of the electricity market (traded energy and price) for an hour, *h*, in which the aggregation of the energy bids required by gathering *N* dwellings in the country has been represented all together over the initial flat part of the demand curve ($WDh = \sum WGRID\ h$). The representative hourly dwelling demand (purchased from the grid) for 2019 in Fig. 7 c) has been retrieved from the web page of REE (REE ESIOS a). Finally, Fig. 7 d) shows the amount of traded energy by technologies and the corresponding volume of $CO_{2\text{-eq}}$ for an hour, *h*.

The volume of CO2-eq emissions corresponding to the hour *h*, *VCO2 h*, has been calculated by examining the list of dispatched generators, as

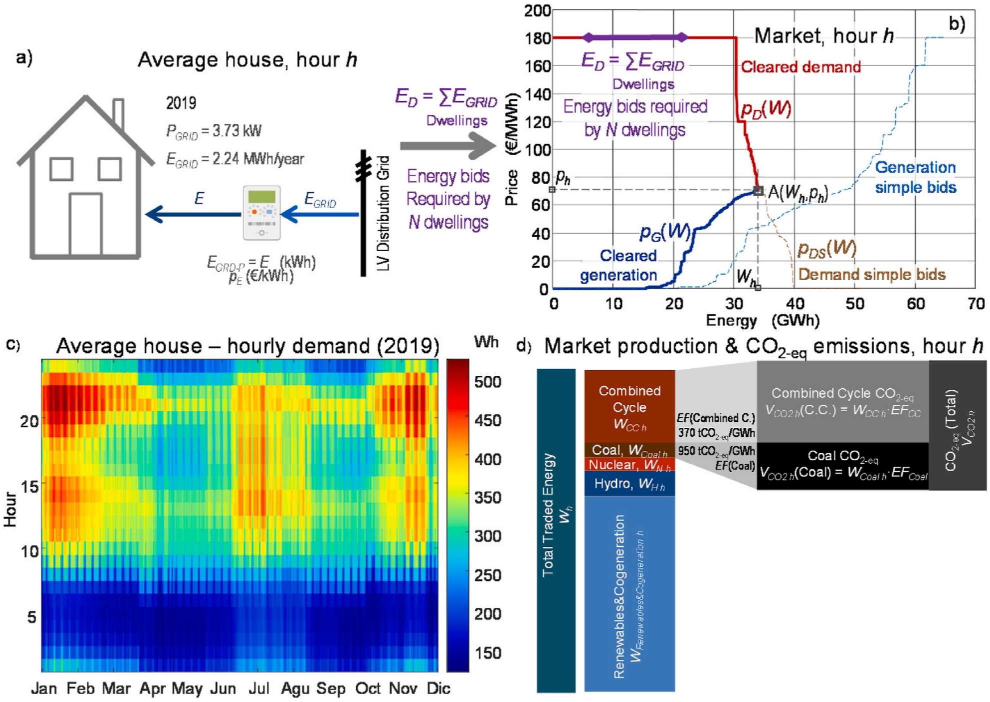


Fig. 7. a) Scheme of the reference scenario, b) market clearing point for an hour, *h*, c) hourly energy required by an average dwelling in 2019, d) traded energy (by technologies) and volume of CO2-eq emissions due to the traded energy in the market corresponding to hour, *h*.

sketched in Fig. 7 d). To do this, it is necessary to identify the technology (TEC) and the amount of energy, *WTEC h*, of each generator, dispatched to produce the energy traded for that hour, *Wh*, so that:

$$W_h = \sum_{TEC} W_{TEC\ h}$$

Finally, the hourly amount of CO2-eq emissions, *VCO2 h*, can be calculated considering the emission factor (REE, 2020b), *EFTEC* (tCO2-eq/GWh), corresponding to each fuel-fired production technology (Appendix A):

$$V_{CO_2\ h} = \sum_{TEC} W_{TEC\ h} \cdot EF_{TEC}$$

For the *NH* hours of a year, the volume of CO2-eq emissions can be determined as:

$$V_{CO_2} = \sum_{h=1}^{NH} \sum_{TEC} W_{TEC\ h} \cdot EF_{TEC}$$

3.3. Household PV self-production

The interactive tool Photovoltaic Geographical Information System (PVGIS, 2020) has been used to elaborate on the hourly household PV self-production profile of a dwelling, located in the centre of the Iberian Peninsula (near Madrid). In order to obtain realistic results, a small commercial PV grid-connected kit of only 1 kWp per dwelling was considered. Fig. 8 a) shows hourly PV self-production corresponding to a 1 kWp facility. Fig. 8 b) shows the new clearing point of the electricity market (traded energy and price) for an hour, *h*, in which the distributed PV self-consumption at country level, has been turned into a demand reduction. The aggregation of the energy bids no longer required by the set of *N* dwellings, provided with PV kits in the country, has been marked all together over the initial flat part of the demand curve (ΔE_{SC}). Fig. 8 c) shows the hourly PV production of the considered 1 kWp facility over the course of a year, determined by means of PVGIS. Finally, Fig. 8 d) shows the amount of traded energy (by technologies) and CO2-eq emissions, corresponding to the hour, *h*, as well as their corresponding reductions due to the reduction in demand in the market, caused by self-production.

The elaboration of this figure requires certain intermediate steps to determine the necessary data. First of all, inter-marginal hydro units, corresponding to the hour, *h*, of the self-consumption scenario (Fig. 8 b)), have to be identified and re-dispatched in the aggregated generation curve, using the method described in Sub-section 3.1.1. Second, following the procedure explained in subsection 3.2, the amount of CO2-eq emissions, corresponding to the hour, *h*, of the self-consumption scenario, *VCO2 SC h*, can be calculated by identifying the amount of energy, *WTEC SC h* and production technologies of every generator dispatched by the market operator, as well as their corresponding emission factors (tCO2-eq/GWh):

$$V_{CO_2\ SC\ h} = \sum_{Technologies} W_{TEC\ SC\ h} \cdot EF_{TEC}$$

Then, the decarbonisation effect, Δ*VCO2 h*, that is, the amount of avoided CO2-eq emissions caused by self-consumption, for the hour, *h* (Fig. 8 b), can be calculated by comparison with the original emissions:

$$\Delta V_{CO_2\ h} = V_{CO_2\ h} - V_{CO_2\ SC\ h}$$

Consequently, that amount of CO2-eq emissions that have been avoided, can be represented as the corresponding point in Fig. 8 d). Repeating this procedure, the determination of the amount of CO2-eq emissions, corresponding to a full one-year period of the self-consumption scenario, can be calculated as:

$$V_{CO_2\ SC} = \sum_{h=1}^{NH} \sum_{TEC} W_{TEC\ SC\ h} \cdot EF_{TEC}$$

and the annual decarbonisation effect, Δ*VCO2*, can be calculated by comparison with the original emissions, *VCO2*, as:

$$\Delta V_{CO_2} = V_{CO_2} - V_{CO_2\ SC}$$

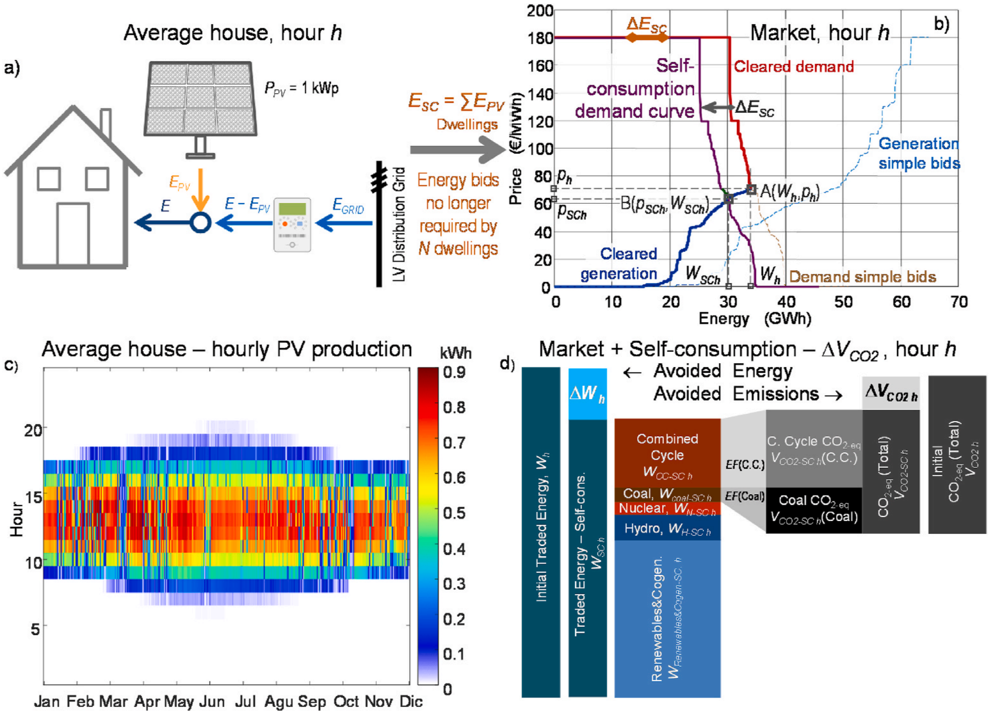


Fig. 8. a) Scheme of a PV self-production scenario, b) new market hourly clearing point of the corresponding PV self-production scenario for the hour, *h*, c) hourly self-production of a house with a 1 kWp PV kit, d) reduction of traded energy and CO2-eq emissions due to the reduction in demand in the market, caused by self-production corresponding to the hour, *h*.

4. Results and discussion

This section presents an analysis of the initial market situation, paying special attention to the actual market clearing points, the generation share by technologies and the resulting CO_2 emissions. Subsequently, details of three considered household PV self-consumption scenarios and their impact on the market are presented. A short discussion of the results and the decarbonisation effect of self-consumption close the section.

4.1. Analysis of the initial situation

The initial situation or BAU corresponds to the actual results of the Iberian market. Fig. 9 a) shows a sketch of the BAU situation in which the considered houses withdraw and purchase all the electricity for the grid. Fig. 9b) and c) show the actual hourly clearing price and traded energy in the Iberian market during 2019 (OMIE, 2021b).

After the assessment of every hourly set of dispatched generators, the hourly amount of energy and the technology of each generator, dispatched for each of the $NH = 8760$ h of 2019, were identified. Finally, following the procedure in Sub-section 3.3, the hourly volume of CO2-eq emissions in 2019 are determined and represented as a heat map in Fig. 9 d).

The identification of hourly production, generated with coal and combined cycle technology in 2019 allows the elaboration of the fuel-based generation heat maps, shown in Fig. 10. This figure shows that coal-based plants produce more during the first quarter of the year, while combined cycle plants do so during the second half of the year. This figure also shows that coal plants have a fairly flat production profile during the day, while combined cycle generators tend to produce more during daylight hours than during night hours.

Fig. 11 shows the maps of the fuel-based (coal + combined cycle) generation and their corresponding CO_2 emissions during 2019. Since the production of combined cycles in 2019 was more than four times higher than that of coal, the daily and seasonal production profiles of Fig. 11 a) are very similar to those in Fig. 10 b), although coal production leaves its mark during the first months of the year. The more intense participation of coal generators during the first quarter of the year also reveals an increase in emissions, which exhibits another rebound during the warmer months of the year (second fortnight of June and first of July).

Fig. 12 shows the annual traded energy in the Iberian daily electricity market and its breakdown by technology for the four-year period 2016–2019. This figure has been calculated by examining the results of the 1,461 day-ahead market's sessions from 1st January 2016 to 31st December 2019. More precisely, by analysing the dispatched generation units in each of the 35,064-hourly time slots of the day-ahead market during the considered four-year period, it is possible to identify their corresponding production technology, as well as the amount of energy produced.

Overall, from the graph, it is evident that there was a significant contribution from renewable energy and cogeneration (the Spanish regulation considers production from renewables, high-efficiency cogeneration and waste in a single category) with an average quota of 68%. Moreover, there was a slight upward trend in the energy produced by renewables over the period in question (2.08 TWh/year).

Nevertheless, coal (15%) and combined cycle (13%) generators still play an important role in the Iberian electricity market, sharing an average 28% of the traded energy in the market. This means that the decarbonisation margin of the Iberian electrical system is still significant. Fig. 12 also shows that fuel-fired (coal + combined cycle) generation is the second-largest contributor, which reached a peak in 2017. There was low rainfall during this year, therefore, the hydro generation underwent a significant reduction that was partially covered by fuel-fired generation.

Hydro and fuel-fired generation, especially combined cycle generation, suggest a kind of complementarity, since years of scarce rainfall has led to the expected reduction of the hydro quota, which often causes the thermal share to rise, covering the lack of hydro production.

4.2. Self-consumption scenarios

The total number of dwellings in Spain reached 25.25 million in

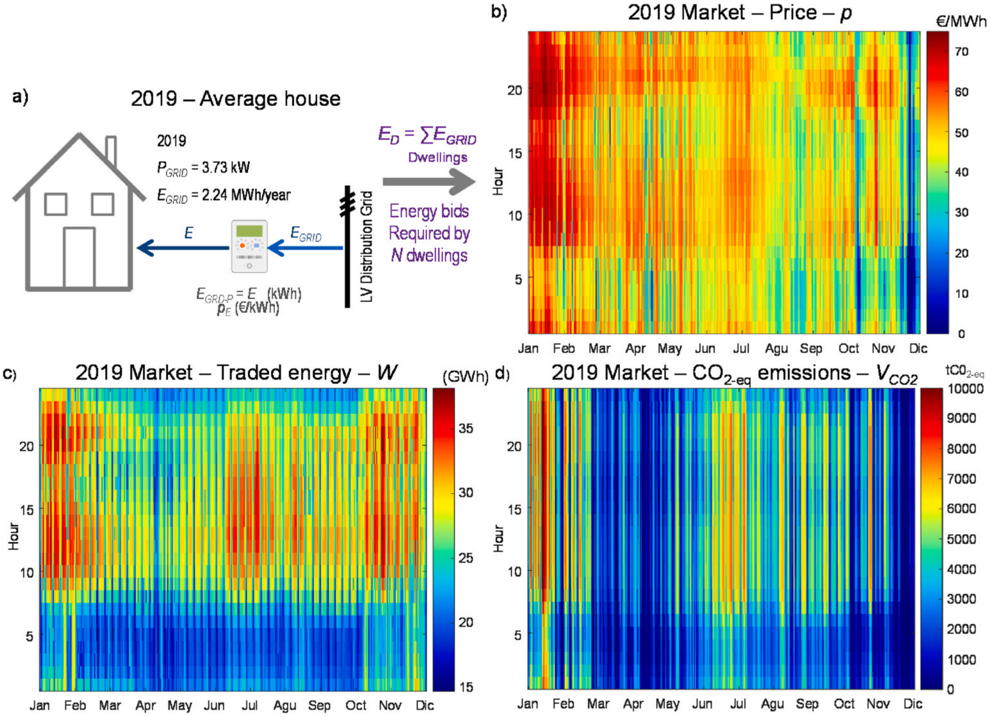


Fig. 9. a) Scheme of the reference scenario, b) results of the market hourly clearing price, c) hourly traded energy and d) hourly volume of CO2-eq emissions in 2019.

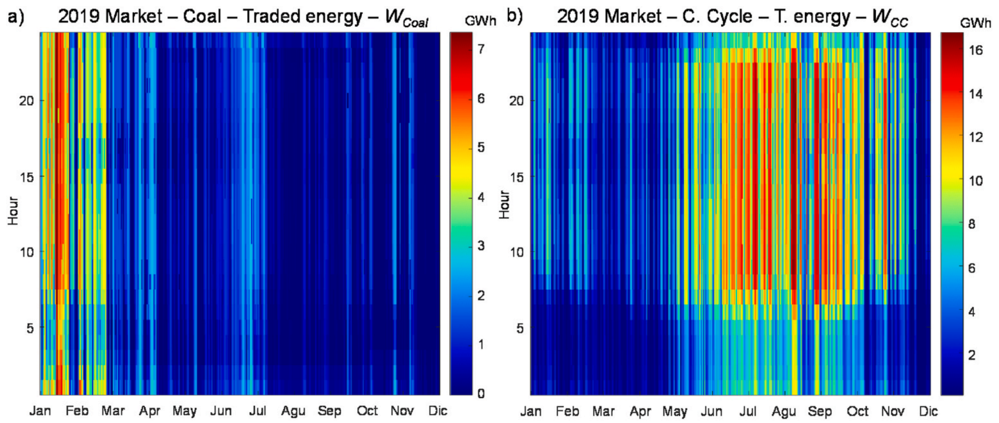


Fig. 10. a) Hourly traded energy based on coal and combined cycle b) in the Iberian market during 2019.

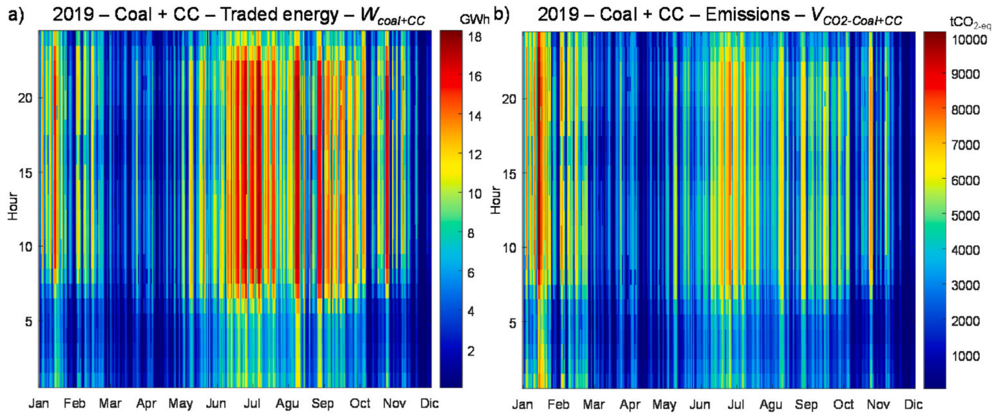


Fig. 11. Results of the hourly traded energy based on a) fuel-based production (coal + combined cycle) and b) the corresponding volume of $CO_{2\text{-eq}}$ emissions in the Iberian/Spanish market during 2019.

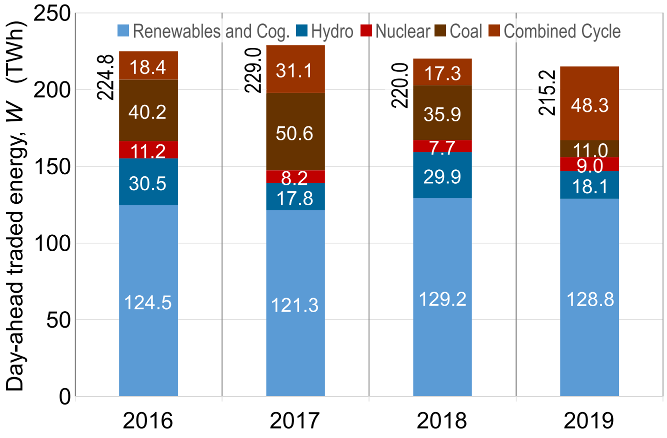


Fig. 12. 2016–2019. Annual traded energy in the Iberian day-ahead market and breakdown by technologies.

2011 (INE, 2019), the last census available. Since then, the number of dwellings has remained almost constant, as shown in Fig. 13 (MFE, 2019). Approximately 33.5% of these homes are detached or semi-detached houses (Eurostat, 2019). This means that during the period 2016–2019, around 8.59 million houses could have included PV generation for self-consumption in Spain.

Three household PV self-consumption scenarios have been considered:

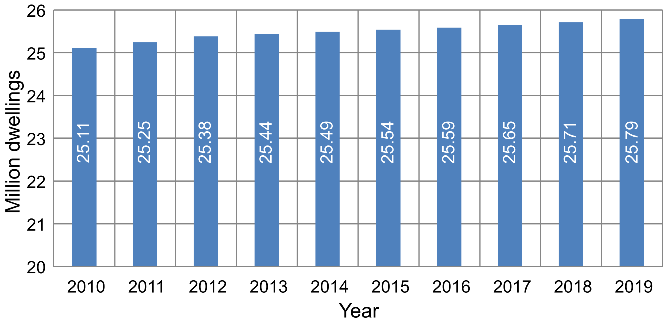


Fig. 13. 2010–2019 Evolution of the number of dwellings in Spain.

- Scenario 1 (15% of dwellings): 1256 thousand houses (detached or semi-detached houses) equipped with a connected-grid PV generator kit of 1 kWp/dwelling
  - Total PV capacity: $P_{PVp} = 1256$ MWp
  - Total annual domestic PV production for self-consumption: $\Delta E_{SC} =$ 2124 GWh, 0.91% of the 2016–2019 average annual traded energy
- Scenario 2 (30% of dwellings): 2512 thousand houses equipped with a PV generator kit of 1 kWp/house
  - Total PV capacity: $P_{PVp} = 2512$ MWp
  - Total annual domestic PV production for self-consumption: $\Delta E_{SC} =$ 4448 GWh, 1.81% of the traded energy for the base case
- Scenario 3 (50% of dwellings): 4188 thousand houses equipped with a PV generator kit of 1 kWp/dwelling
  - Total PV capacity: $P_{PVp} = 4188$ MWp

- Total annual domestic PV production for self-consumption: $\Delta E_{SC} =$ 7080 GWh, 3.02% of the traded energy for the base case

It is worth mentioning that the scenarios considered are rather conservative, since only individual domestic self-consumption, with a small commercial grid-connected PV power kit of only 1 kWp per dwelling, was considered.

4.3. Impact of self-consumption of CO_2 emissions

As previously highlighted, the development of a certain amount of PV prosumer activity, that is, the residential self-consumption of PV self-produced energy, distributed throughout the country, results in a reduction in demand in the market. Fig. 14 a) shows an overview of the self-consumption in Scenario 2. This way, the PV electricity production in daylight hours is self-consumed in the house, which reduces the amount of energy withdrawn and purchased from the grid in the daytime. Using actual market data from the period 2016–2019 and translating the hourly distributed PV self-consumption into a reduction of hourly demand bids, as well as reproducing the market clearing process following the methodology explained in Sub-section 3.1, the new clearing points and the dispatched generators are determined.

As an example, Fig. 14 b) shows the differences between the initial hourly prices in the Iberian market and the hourly prices corresponding to the self-consumption scenario throughout 2019. Similarly, Fig. 14 c) shows the corresponding reduction in traded energy.

Finally, an examination of every hourly set of dispatched generators, corresponding to the self-consumption scenario, allows the identification of the hourly amount of energy dispatched, as well as the technology of each dispatched generator. Following the procedure in Sub-section 3.3, the differences between the hourly volume of CO2-eq emissions corresponding to the self-consumption scenario and the actual emissions in the Iberian/Spanish market during 2016–2019 are calculated; the results, corresponding to 2019, are illustrated as a colour-map in Fig. 14 d). Table 1 summarizes the annual fuel-fired traded energy in the market and the corresponding volume of $CO_{2\text{-eq}}$ emissions for the period 2016–2019 in the BAU.

Fig. 15 summarizes the results corresponding to the reduction of the annual traded energy in the market corresponding to the household self-consumption scenarios. As a result of the rebound effect or efficiency paradox shown, the percentage of reduction in traded energy (energy which is no longer necessary to be dispatched in the market) with respect to the amount of self-consumed energy, $\Delta W(\Delta Esc)/\Delta Esc$, is around 75% in the case of Scenario 1 (15% houses) and decreases gradually at a rate of 0.8% for each TWh of self-consumed energy (Table B1 in Appendix B). Nevertheless, the percentage reduction of fuel-fired (coal + combined cycle) production with respect to the reduction of the traded energy in the market ($\Delta W_{Coal\ +\ C.\ Cycle}/\Delta W$), is around 41% for Scenario 1 and grows at a rate of 4.1% for each TWh of self-consumed energy (Appendix B).

As previously mentioned, the rebound effect can be explained as the response of certain flexible consumers, who are willing to acquire their energy at a lower price. Although electricity is a poorly substitutable good and the demand curve is rather inelastic, it is, nevertheless, not a completely vertical line, as shown in Fig. 5. Some consumers, often large industrial consumers, are capable of self-producing or substituting a fraction of their demand at a certain price level. Accordingly, the demand bids of these industrial consumers are placed in the central band of prices. Therefore, when the clearing price is low enough, some of these consumers (those whose demand bids are between points A and A′ in Fig. 5 b)), are encouraged to buy more electricity. As a result, the decrease of the hourly traded energy in the market is less than the reduction of the residential consumers' bids, due to self-consumption.

Fig. 16 presents the evolution of the average of hourly traded energy during the daytime, for the considered four-year period. The solid line represents the base-case, that is, the actual results of the market (without PV self-consumption). The figure suggests that the energy reduction, corresponding to the new self-consumption scenarios, tends to push down the original traded energy profile, reducing the peak (daytime) and decreasing the average traded energy. Moreover, the average peak demand in the daytime (produced around 13:00–14:00 h) is clearly diminished by self-consumption scenarios. For instance, the daytime

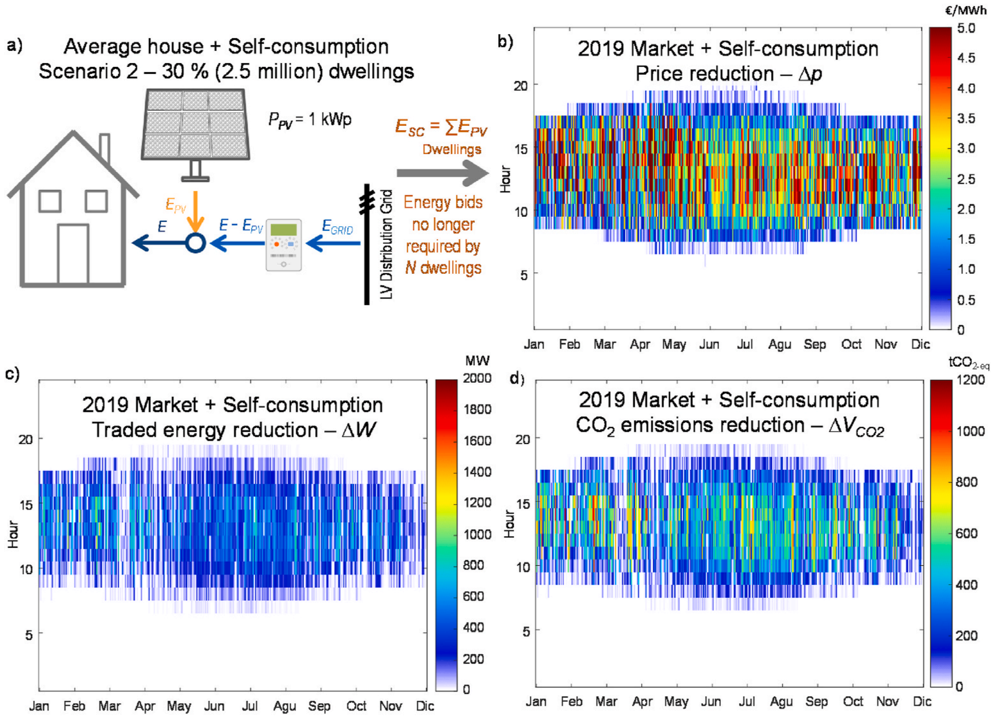


Fig. 14. Scenario 2–30% (2.51 million) houses – 2019. a) scheme of a household grid-connected PV self-consumption scenario, reduction of the market hourly clearing price b), hourly traded energy, c) and d) hourly volume of CO2-eq emissions.

Table 1
(BAU: 2016–2019) Annual fuel-fired (coal and combined cycle) traded energy in the market and volume of emissions.

	Fuel-fired energy			$CO_{2\text{-eq}}$ emissions		
Year	W_{Coal} (TWh)	W_{CC} (TWh)	$W_{Coal+CC}$ (TWh)	$V_{CO2\ Coal}$ ($tCO_{2\text{-eq}}$)	$V_{CO2\ CC}$ ($tCO_{2\text{-eq}}$)	$V_{CO2\ Coal+CC}$ ($tCO_{2\text{-eq}}$)
2016	39.39	17.00	57.39	$37.42{\cdot}10^6$	$6.66{\cdot}10^6$	$44.08{\cdot}10^6$
2017	50.24	30.55	80.79	$47.73{\cdot}10^6$	$11.30{\cdot}10^6$	$59.03{\cdot}10^6$
2018	36.05	17.30	53.35	$34.25{\cdot}10^6$	$6.40{\cdot}10^6$	$40.65{\cdot}10^6$
2019	10.33	48.38	58.71	$9.82{\cdot}10^6$	$17.90{\cdot}10^6$	$27.72{\cdot}10^6$
Average	34.00	28.56	62.56	$32.30{\cdot}10^6$	$10.57{\cdot}10^6$	$42.87{\cdot}10^6$

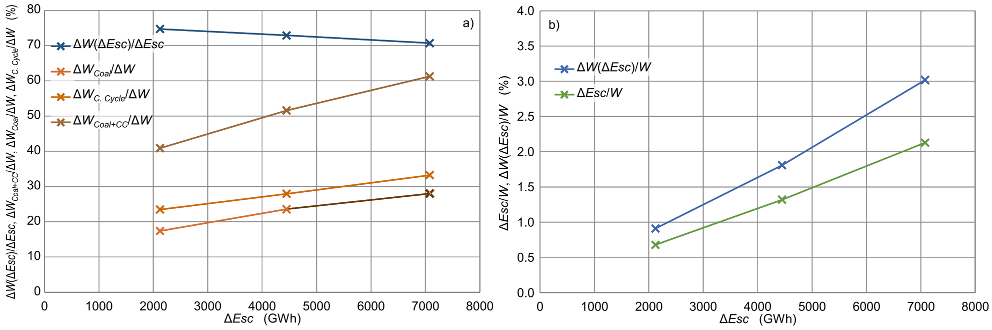


Fig. 15. Average of the period 2016–2019. Evolution of the self-consumed energy of a) the relative reductions of traded energy, coal generation, combined cycle generation, total fuel-fired generation and b) the relative self-consumed energy and the reduction of the traded energy.

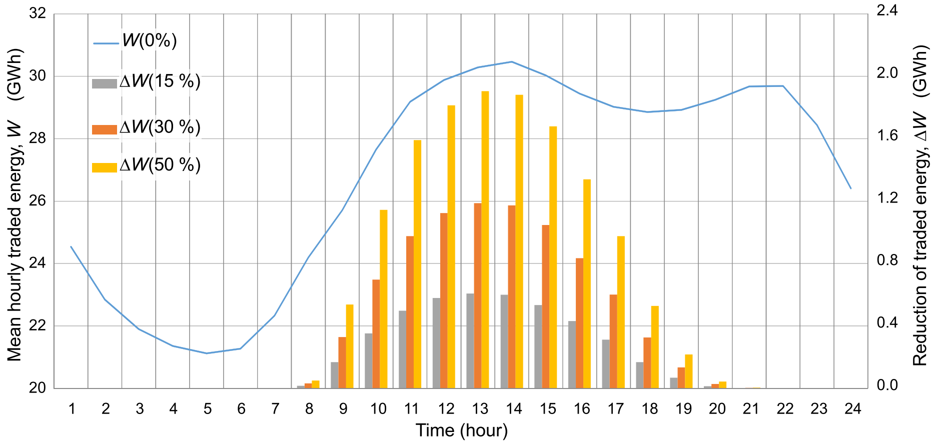


Fig. 16. 2016–2019. Average hourly traded energy in the market and average reduction of the hourly traded energy across different scenarios of self-consumption.

peak level of 30.5 GWh at 14:00 experiences an average reduction of 0.60 GWh (1.97% of peak value) in the case of Scenario 1 (15% of houses), 1.17 GWh (3.85%) in Scenario 2 (30% of houses) and 1.88 GWh (6.17%) in Scenario 3 (50% of houses). The corresponding data regression line (Appendix B) shows that self-consumption reduces the peak demand with a rate of 258.2 MWh per TWh of annual domestic self-consumed energy.

Tables 2 and 3 summarize the results corresponding to the annual reductions of traded energy and the annual reductions in the volume of $CO_{2\text{-eq}}$ emissions, corresponding to the three scenarios for the four-year period 2016–2019.

The results of Table 2 show that the reduction of fuel-fired (coal and combined cycle) productions ($\Delta W_{C+C.\ Cycle}(\Delta Esc)$) is 649 GWh for Scenario 1 (15% of houses) and grows at an average rate of 489.4 MWh for

Table 2
Annual reduction of the traded fuel-fired energy, by technology, in the day-ahead electricity market, corresponding to the considered household PV self-consumption scenarios.

	Scenario 1 (15% of houses)			Scenario 2 (30% of houses)			Scenario 3 (50% of houses)		
	Self-consumption $\Delta E_{SC} = 2124$ GWh/year			Self-consumption $\Delta E_{SC} = 4447$ GWh/year			Self-consumption $\Delta E_{SC} = 7080$ GWh/year		
Year	ΔW_{Coal} (GWh)	ΔW_{CC} (GWh)	$\Delta W_{Coal+CC}$ (GWh)	ΔW_{Coal} (GWh)	ΔW_{CC} (GWh)	$\Delta W_{Coal+CC}$ (GWh)	ΔW_{Coal} (GWh)	ΔW_{CC} (GWh)	$\Delta W_{Coal+CC}$ (GWh)
2016	366	211	577	894	504	1398	1415	1270	2684
2017	321	386	707	862	897	1759	1691	1691	3382
2018	282	165	447	817	417	1234	1321	1310	2631
2019	136	728	864	350	1649	1999	1183	2386	3569
Average	276	373	649	731	867	1598	1402	1664	3067

Table 3
Annual reduction of the volume of carbon dioxide emissions in the day-ahead electricity market, corresponding to the considered household PV self-consumption scenarios.

	Scenario 1 (15% of houses)			Scenario 2 (30% of houses)			Scenario 3 (50% of houses)		
	Self-consumption $\Delta E_{SC} = 2124$ GWh/year			Self-consumption $\Delta E_{SC} = 4447$ GWh/year			Self-consumption $\Delta E_{SC} = 7080$ GWh/year		
Year	$\Delta V_{CO2\ Coal}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ CC}$ $tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ Coal+CC}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ Coal}$ $tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ CC}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ Coal+CC}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ Coal}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ CC}$ ($tCO_{2\text{-eq}}$)	$\Delta V_{CO2\ Coal+CC}$ ($tCO_{2\text{-eq}}$)
2016	$348 \cdot 10^3$	$78 \cdot 10^3$	$426 \cdot 10^3$	$849 \cdot 10^3$	$187 \cdot 10^3$	$1036 \cdot 10^3$	$1344 \cdot 10^3$	$470 \cdot 10^3$	$1814 \cdot 10^3$
2017	$305 \cdot 10^3$	$143 \cdot 10^3$	$448 \cdot 10^3$	$819 \cdot 10^3$	$332 \cdot 10^3$	$1151 \cdot 10^3$	$1607 \cdot 10^3$	$626 \cdot 10^3$	$2232 \cdot 10^3$
2018	$268 \cdot 10^3$	$61 \cdot 10^3$	$329 \cdot 10^3$	$776 \cdot 10^3$	$154 \cdot 10^3$	$930 \cdot 10^3$	$1255 \cdot 10^3$	$485 \cdot 10^3$	$1739 \cdot 10^3$
2019	$129 \cdot 10^3$	$269 \cdot 10^3$	$398 \cdot 10^3$	$332 \cdot 10^3$	$610 \cdot 10^3$	$942 \cdot 10^3$	$1124 \cdot 10^3$	$883 \cdot 10^3$	$2007 \cdot 10^3$
Average	$262 \cdot 10^3$	$138 \cdot 10^3$	$400 \cdot 10^3$	$694 \cdot 10^3$	$321 \cdot 10^3$	$1015 \cdot 10^3$	$1332 \cdot 10^3$	$616 \cdot 10^3$	$1948 \cdot 10^3$

each TWh of self-consumed energy (Table B3 - Appendix). The rate of reduction in the annual volume of CO_2 emissions, due to fuel-fired generation ($\Delta V_{CO2\ Coal+CC}(\Delta Esc)$), is around 262 thousand tons of $CO_{2\text{-eq}}$ for Scenario 1 (15% of houses) and grows at an average rate of 313.2 $tCO_{2\text{-eq}}$ for each TWh of self-consumed energy (Table B3 - Appendix).

5. Discussion

The main limitations and uncertainties of the work may be related to the aforementioned simplified method of reproducing the performance of the Market Operator and to the evaluation of the nation-wide aggregation of household PV self-consumption. The simplified clearing the market methodology was advisable due to the large amount of markets (35064 market hourly time slots) in the four-year scenario (2016–2019) considered in this work. However, the deviations in the results should not be significant due to the relatively small amount of PV self-consumption (percentage of the traded energy) and to the large number of market clearing operations, which could compensate the possible errors. On the other hand, the nation-wide distributed domestic PV self-production has been evaluated based on the hourly production of a single dwelling on average conditions for Spain. That is, a house located in the centre of the country (nearby Madrid). The Iberian Peninsula has a shape similar to that of a rectangle that measures about 900 km width, from east to west, and about 1,000 km high, from north to south. This means that there is a (maximum) difference in solar time of about 45 min between the eastern and western latitudes of peninsular Spain, which may slightly affect the value of the nation-wide distributed domestic PV self-production. But other factors, such as the differences in weather conditions over the Iberian Peninsula or the usual variations in the rainfall regime (hydro generation) or in temperatures (electricity demand) from one year to the next, may also affect the results.

Figueiredo et al. (2019) analysed the phase-out of the two remaining coal-fired power plants in Portugal. Using data of 2015 they found, among other things that coal plants with a total capacity of 1.7 GW and an annual production of 13.74 TWh (28% of the Portuguese generation mix) could be replaced by about 8 GW of PV if accompanied by a modest increase in the already existing hydro pump capacity. The PV scenario reduces would reduce the volume of $CO_{2\text{-eq}}$ emissions a 51%, from 20.4 $MtonCO_{2\text{-eq}}$ to 10.4 $MtonCO_{2\text{-eq}}$. Using the PVGIS tool (PVGIS, 2020), we have estimated the annual production corresponding to the 8 GW PV scenario at 12.46 TWh. Therefore, the PV scenario reduces the volume of emissions by 10.4 $MtonCO_{2\text{-eq}}$/12.46 TWh = 834.7 $tonCO_{2\text{-eq}}$ for each GWh/year of PV production. This rate of reduction of the volume of emissions is about 2.7 times higher than our average rate of 313.23 $tCO_{2\text{-eq}}$ for each GWh/year of self-consumed energy, but this is not a ceteris paribus comparison: although Portugal and Spain share the common Iberian Market, PV self-consumption is not the same that PV generation, data correspond to different periods of time (2015 in the Portuguese PV generation case and 2016–2019 for the Spanish self-consumption), the share of coal in the Portuguese system (28% in 2015) is higher than in the Spanish mix (reducing from 14,2% in 2016 to 4.3% in 2019, with an average value of 12.4% in the four-year period). Probably this significate difference in the shares of coal in their respective systems may explain the difference in the rates of reduction of the volume of emissions (the quotient of coal shares 28/12.4 = 2.3 approaches the quotient of rates of emissions reduction 834.7/313.2 = 2.7).

According to basic market rules, self-consumption by residential consumers decreases aggregate demand, causing the price to drop. This price reduction drives flexible consumers (often large industrial consumers) to purchase a little more energy from the market. As a result, the removal of the traded energy in the market, ΔW(ΔEsc), is less than the amount of energy which is no longer necessary, due to PV self-consumption, ΔEsc. As previously mentioned, the reduction of the traded energy in the market is around 75% of the self-consumed energy ($\Delta W(\Delta Esc)/\Delta Esc \approx 0.75 \cdot \Delta Esc$) in the case of Scenario 1 (71% for Scenario 3). As a consequence, the remaining 25% (29% for Scenario 3) corresponds to the rebound effect: an increase in the demand for those flexible consumers who can adapt their energy needs to the price reduction.

On the other hand, the considered scenarios are rather conservative, especially with regard to the PV power installed in homes. Individual family dwellings are often inhabited by families with a rather high economic status. These kinds of families often have higher than average energy consumption, making it advisable to equip their homes with a PV self-consumption kit of higher peak power, to better satisfy their consumption. As an example, a study on EU prosumers estimates that the potential residential solar PV capacity of Spain is 13.4 GW (Prosumers, 2017). Otherwise, the amount of self-produced PV energy, ΔEsc, has been transferred as an equivalent amount of the reduction of purchase bids in the market, $\Delta Esc_{bids} = \Delta Esc$. However, the amount of self-produced energy does not have to flow through the transmission-distribution network, avoiding the corresponding electrical losses, $p_{LT\text{-}D}$. Consequently, the decrease in household demand, due to PV self-consumption, should be transferred to the market as a reduction equivalent to ΔEsc and avoided losses. That is, the demand reduction, due to PV self-consumption, ΔEsc, should become a reduction of $\Delta Esc/(1 - p_{L\ TD})$ in the purchase bids in the market. For a typical value $p_{L\ TD} \approx 7\%$, this means a reduction in the purchase bids of 7.5% more than the self-consumed PV energy, $\Delta Esc_{bids} \approx 1.0753 \cdot \Delta Esc$, which constitutes a third of the rebound effect.

PV household self-consumption, by changing the market clearing point, causes rent transfers among market agents, which even extend beyond national borders to other systems, through international interconnection lines:

- between generation and demand. There is an income transfer from generators (including hydro units), which sell less energy at a lower price to consumers, who could purchase their energy at a lower cost.
- between generators. In relative terms, from fuel-fired generators, which reduce their income, especially those thermal units which are excluded from the market because their production is no longer necessary, to renewable generators, especially hydro units which are

flexible enough to remain dispatched, even in the new market situation.

- between consumers. In relative terms, from domestic consumers who install a PV self-production kit and who play the role of active actors in this work, to the whole set of consumers, who can purchase their energy at a lower cost. However, especially in relation to flexible consumers who can profit from buying more energy at a lower price.

Since hydro units are marginal for almost half of the hours of the year in the Iberian/Spanish market, the reduction in aggregated demand, due to the integration of small amounts of self-consumption, E_{SC}, has the effect of withdrawing these marginal hydro units. However, as previously mentioned, hydro generators are flexible enough to adapt and stay marginal in that new market situation. Hydro generators face the new demand reduction situation by reducing their selling bids in order to be dispatched again in the new scenario. Consequently, the integration of small amounts of self-consumption, E_{SC}, leads to dispatch orders with an increment of the percentage of renewable (hydro) units and a reduction in the percentage of fuel-fired units, which leads to a reduction in the volume of $CO_{2\text{-eq}}$ emissions. For low self-consumption levels, marginal (or near-marginal) hydro units are re-dispatched. However, as the volume of self-consumption grows, the units withdrawn from the market are increasingly fuel-fired generators, which increase the emission reduction rate. This explains why the rate of reduction of coal and combined cycle generation in Tables 2 and 3 increases with the amount of self-consumption.

At first glance it may seem that household PV self-consumption is similar to the integration of PV generation in the market, however their effects are qualitatively and quantitatively different. Focusing on the decarbonising effect, Fig. 5 b) shows how a certain amount of household PV self-consumed energy translates into a reduction in demand (left-shifting of the demand curve), which gives rise, between other things, to a reduction in the amount of the traded energy in the market. That reduction in demand made the production of certain fuel-fired units no longer necessary, leading to a reduction of $CO_{2\text{-eq}}$ emissions. On the contrary, the integration of an equivalent amount of PV generation shifts to the right the generation curve, leading to an increase in the traded energy in the market (the opposite effect). Although this increase corresponds mainly to integrated PV energy, the removal of fuel-fired units is not as efficient as in the PV self-consumption case.

This difference would encourage policymakers to develop policies favouring the deployment of PV self-consumption since the decarbonisation effect of PV self-consumption is greater than that of large PV plants. On the other hand, the reduction in demand in the market for self-consumption would help to comply with Spanish national obligations with the objective of efficiency and the reduction of the Spanish energy import rate (higher than the EU average). In addition, although home PV systems have higher unit costs (€/kWp), families that choose to install a PV kit in their homes are not usually as concerned about their economic profitability as might be the owners or shareholders of large PV plants.

6. Conclusions

Using a ceteris paribus approach, this work has analysed and quantified the potential impact of three household PV self-consumption scenarios on the Iberian market, including the identification of the technology of the generation units, the production of which is no longer necessary, due to the demand contraction induced by household PV self-consumption.

The main results of this work, based on actual hourly market data for the four-year period 2016–2019, suggest that:

- for Scenario 1 the percentage of the reduction of traded energy in the market with respect to the amount of self-consumed energy, $\Delta W (\Delta Esc)/\Delta Esc$, is around 75% (25% rebound effect), reduced to a rate of 0.8% for each TWh/year of self-consumed energy.
- for Scenario 1 the reduction of the volume of emissions due to fuel-fired generation, $\Delta V_{CO2\ C+C.\ Cycle}$, is 400.2 thousand tons of $CO_{2\text{-eq}}$ and grows with an average rate of 313.23 $tCO_{2\text{-eq}}$ for each GWh/year of self-consumed energy.

On average, while the annual percentage of self-consumed energy, $\Delta Esc/W$, grows linearly from 0.91% (Scenario 1) to 3.03% (Scenario 3), the percentage reduction of the volume of emissions due to fuel-fired generation, $\Delta V_{CO2\ C+C.\ Cycle}/V_{CO2\ C+C.\ Cycle}$, grows from 0.93% to 4.54% of the corresponding volume of emissions. In other words, there is an amplification factor, ranging from 1.03 to 1.51, between the annual percentage of self-consumed energy, $\Delta Esc/W$, and the percentage reduction of the volume of emissions, due to fuel-fired generation, $\Delta V_{CO2\ C+C.\ Cycle}/V_{CO2\ C+C.\ Cycle}$. This amplification effect confirms household PV self-consumption as a suitable and powerful tool for decarbonising the electricity market.

Even though the background of this study has been the Spanish renewable self-consumption regulation, the approach of the issue is quite general and could be applied to regulations in other countries, especially to those in the EU region. The proposed methodology could also act as a tool for policymakers to assess the potential decarbonisation effect of renewable self-consumption, according to their different national regulations.

To conclude, household PV self-consumption, despite the rebound effect and besides the reduction in the volume of $CO_{2\text{-eq}}$ emissions analysed in this work, could also help reduce the energy losses in the transmission system, as well as avoid or delay congestion problems at peak hours. Home PV self-consumption turns consumers into prosumers, offering common individual citizens the opportunity to play an active role in the transition to a decarbonised and more resilient energy procurement in their local/national community. Furthermore, the diffusion of self-consumption can act as an accelerator of energy transition since domestic investors are often less demanding regarding the return on their investment than large groups that invest in utility-scale plants. The contraction of fuel-fired generation also makes household PV self-consumption a suitable tool for reducing the high Spanish rate of fuel import dependence and achieving its international climate obligations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Emission factors

Table A1
Values of the emission factors, *EFTEC*, corresponding to each fuel-fired production technology (REE, 2020b).

Coal *EFCOAL* (tCO2-eq/GWh)	Gas *EFGAS* (tCO2-eq/GWh)
950	370

Appendix B. Regression lines

Table B1
Regression lines corresponding to different energy ratios with the amount of self-consumed energy and with the traded energy.

Reduction in traded energy	Coef. of determination	Magnitude	Units	Magnitude	Units
$\Delta W(\Delta Esc) \approx 0.6906 \cdot \Delta Esc + 87.061$	$R^2 = 0.9991$	$\Delta W(\Delta Esc)$	GWh	ΔEsc	GWh
$\Delta W(\Delta Esc)/\Delta Esc \approx -0.0008 \cdot \Delta Esc + 76.442$	$R^2 = 0.9995$	$\Delta W/\Delta Esc$	%	ΔEsc	GWh
$\Delta W_{Coal+CC}(\Delta Esc)/\Delta W(\Delta Esc) \approx 0.0041 \cdot \Delta Esc + 32.605$	$R^2 = 0.9960$	$\Delta W_{Coal+CC}/\Delta W$	%	ΔEsc	GWh
$\Delta W_{Coal}(\Delta Esc)/\Delta W(\Delta Esc) \approx 0.0021 \cdot \Delta Esc + 13.311$	$R^2 = 0.9829$	$\Delta W_{Coal}/\Delta W$	%	ΔEsc	GWh
$\Delta W_{CC}(\Delta Esc)/\Delta W(\Delta Esc) \approx 0.0020 \cdot \Delta Esc + 19.276$	$R^2 = 0.9990$	$\Delta W_{CC}/\Delta W$	%	ΔEsc	GWh
$\Delta Esc/W \approx 0.0004 \cdot \Delta Esc - 0.0274$	$R^2 = 0.9976$	$\Delta Esc/W$	%	ΔEsc	GWh
$\Delta W(\Delta Esc)/W \approx 0.0003 \cdot \Delta Esc + 0.0438$	$R^2 = 0.9990$	$\Delta W(\Delta Esc)/W$	%	ΔEsc	GWh

Table B2
Regression lines corresponding to the average price reduction and the relative price reduction.

Reduction of daytime hourly energy peak	Coef. of determination	Magnitude	Units	Magnitude	Units
$\Delta W_{Peak}(\Delta Esc) \approx 0.2582 \cdot \Delta Esc + 59.612$	$R^2 = 0.9996$	$\Delta W_{peak}(\Delta Esc)$	MWh	ΔEsc	GWh

Table B3
Evolution of the reduction of thermal generation and $CO_{2\text{-eq}}$ emissions, derived from domestic self-consumption.

	Coef. of determination	Magnitude	Units	Magnitude	Units
Reduction of traded energy					
$\Delta W_{Coal+CC}(\Delta Esc) \approx 0.4894 \cdot \Delta Esc - 455.79$	$R^2 = 0.9924$	$\Delta W_{Coal+CC}$	GWh	ΔEsc	GWh
$\Delta W_{Coal}(\Delta Esc) \approx 0.2278 \cdot \Delta Esc - 233.62$	$R^2 = 0.9945$	ΔW_{Coal}	GWh	ΔEsc	GWh
$\Delta W_{CC}(\Delta Esc) \approx 0.2614 \cdot \Delta Esc - 221.58$	$R^2 = 0.9903$	ΔW_{CC}	GWh	ΔEsc	GWh
Reduction of $CO_{2\text{-eq}}$ emissions					
$\Delta V_{Coal+CC}(\Delta Esc) \approx 313.23 \cdot \Delta Esc - 304284$	$R^2 = 0.9933$	$\Delta V_{Coal+CC}$	$10^3 \cdot tCO_{2\text{-eq}}$	ΔEsc	GWh
$\Delta V_{Coal}(\Delta Esc) \approx 96.783 \cdot \Delta Esc - 82229$	$R^2 = 0.9903$	ΔV_{Coal}	$10^3 \cdot tCO_{2\text{-eq}}$	ΔEsc	GWh
$\Delta V_{CC}(\Delta Esc) \approx 216.45 \cdot \Delta Esc - 221984$	$R^2 = 0.9944$	ΔV_{CC}	$10^3 \cdot tCO_{2\text{-eq}}$	ΔEsc	GWh

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