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Research paper

Regulation of photovoltaic prosumer plants: An analysis through a dynamic expression of the avoided cost

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ABSTRACT

Driven by technical advances and favorable regulatory measures (albeit only in some countries), the deployment of electricity generation at very small scales, or micro-generation, is shaping a new segment of the electricity system which has been called "Residential Energy Sector" or "Micro-Generation Sector". Known as "self-production" or "self-consumption" years ago, the main objective of on-site, or demand-side, microgeneration is to provide electricity services to homes and businesses from their own plants. While the concept of avoided cost has been used in the past, a dynamic model which takes into account the different influencing factors has not been previously developed. This paper closes this gap in the literature. It proposes a dynamic, easily replicable model which contains the main factors which influence the avoided costs and facilitates the analysis of the investment decisions taken by residential prosumers. The results show that, compared to other variables, the evolution of retail prices is the most relevant factor affecting the avoided cost, suggesting that their gradual increase could lead to the substitution of plants before the end of their useful life. However, the importance of retail prices and their unknown evolution gives investment decisions on residential plants an inherent uncertain character. Therefore, a higher retail price can encourage the investment by reducing the recovery period. If the accumulated avoided cost equals the initial investment earlier, this reduces both the uncertainty (the period is shorter) and the psychological impact of a strong initial expense. Although regulatory factors (e.g., the existence of subsidies and the conditions of grid exchange) do not have a large economic impact, those factors contribute to the change in the psychological framework which future prosumers will face. In particular, they partly offset the detrimental impact of the initial upfront costs on the decision to invest, even if the revenues and other advantages offset such initial amount of investment.

1. Introduction

Driven by technical advances and favorable regulatory measures (albeit only in some countries), the deployment of electricity generation at very small scales, or micro-generation, is shaping a new segment of the electricity system which has been called "Residential Energy Sector" (Staffell et al., 2015), although "Micro-Generation Sector" is a more comprehensive term. Known as "self-production" or "self-consumption" years ago, the main objective of on-site, or demand-side, microgeneration is to provide electricity services to homes and commercial and industrial businesses from their own plants (Brett and Staffell, 2015; Kelly et al., 2015a).

Those services include lighting, powering of home appliances (including the car which, in turn, can be a source of energy), cooling and heating. Two main aspects of microgeneration are worth highlighting. On the one hand, microgeneration uses very different techniques and fuels (biomass boilers, heat pumps, solar photovoltaic and thermal, fuel cells, etc.). Sometimes these are non-renewable ones, as it is the case with combined micro heat and power (micro-CHP) systems fed by natural gas, and are endowed with storage systems and systems to control electricity flows. On the other hand, several factors change the level of consumption and the type of energy sources being used by the domestic and business actors (Bird et al., 2015). These include factors such as climate, income, household composition, lifestyle, the construction features of buildings, the support of public administrations for investments in equipment and implementation of energy savings and efficiency and the concern of policy makers on climate change, among others. As a result, the traditional

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energy consumer changes its lifestyle (Wittenberg and Matthies, 2018, p.298) and becomes an energy citizen (Goulden et al., 2014, p.22 and 24), i.e., someone who participates, either individually or collectively, directly or indirectly, in the electricity system.

This new reality of microgeneration has boosted a vast literature in recent years. Some contributions have analyzed the economic features of microgeneration with the help of simulation and optimization models (MacGill and Watt, 2015; Moshövel et al., 2015; Lauinger et al., 2016; Opiyo, 2016; Siemer et al., 2016), identifying the conditions and factors which make it more attractive from a system or an adopter point of view. Others have paid attention to its regulatory aspects, i.e., the public policy elements which would enhance its economic feasibility (see, e.g., the reviews of Hoppmann et al., 2014; Kelly et al., 2015a,b; Luthander et al., 2015; Staffell and Hamilton, 2015).

This paper connects to those literatures since it provides an analysis of the economic and regulatory aspects of the investment decisions taken by residential prosumers, focusing on photovoltaic (PV) on-side generation, which was initially defined as the production of electricity by means of panels installed on the customer's side of the meter, that is, on roofs and façades of residential houses, shops, warehouses or industrial buildings (Alanne and Saari, 2006). The size of these PV plants is currently below 10 kW in case of dwellings and below 25 kW for non-residential installations such as shops, small workshops and warehouses, etc. (Mir-Artigues and del Río, 2016, p.243). The goal of such generators is currently self-consumption. However, there might also be plants with much higher capacities, even up to 500 kW, e.g., shopping malls, industrial warehouses, etc. which will be prone to sell the generated electricity in the market.

Those installations are increasingly including batteries and, in a not too distant future, they can be expected to include equipment for the management of demand, which makes up a complex plant at a very small scale. Energy savings and energy efficiency measures can be added to this plant, including the improvement of the insulation of the building (walls and windows), the optimization of lighting points, the installations of LEDs etc. This is a segment within the micro-generation sector, which is identified as micro-Photovoltaic Generation (mPVG), which is the focus of this paper.

A mPVG plant is a non-negligible techno-economic complex. As suggested before, mPVG is based on three pillars: the availability of domestic storage systems, where the traditional lead–acid batteries have been replaced by the lithium-ion ones, whose price can go down from $700/kWh in 2013 to $300/kWh between 2020–2025 (IEA-RETD, 2014, p.34, Ding et al., 2015), the implementation of systems to manage their own demand and the possibility of exchanges with the grid according to a specific regulation. Although these three options can be combined in pairs, they might appear jointly, as shown in Fig. 1. Furthermore, mPVG displays all its potential advantages if it operates in the environment of a smart grid (IEA-RETD, 2014; Skjolsvold et al., 2015) and appropriate market structures develop (see O'Shaughnessy et al., 2018; Falabretti et al., 2018; van der Stelt et al., 2018).

Two ratios are important in evaluating the performance of an mPVG plant: the self-consumption rate (SCR) and the self-sufficiency rate (SSR). Firstly, prosumers may be willing to reach the highest SCR, that is, the part of the self-produced electricity which is consumed on-site, defined for a long period of time (a year, for example) (adapted from Luthander et al., 2015, p.82, Mir-Artigues and del Río, 2016, p.249, Castillo-Cagigal et al., 2011, p.6). This volume can be disaggregated into the part which is instantaneously consumed on-site and the portion of consumption which is delayed (because it has been stored).

Secondly, the SSR ratio is defined as the proportion between the on-site load and the electricity generated by the installation

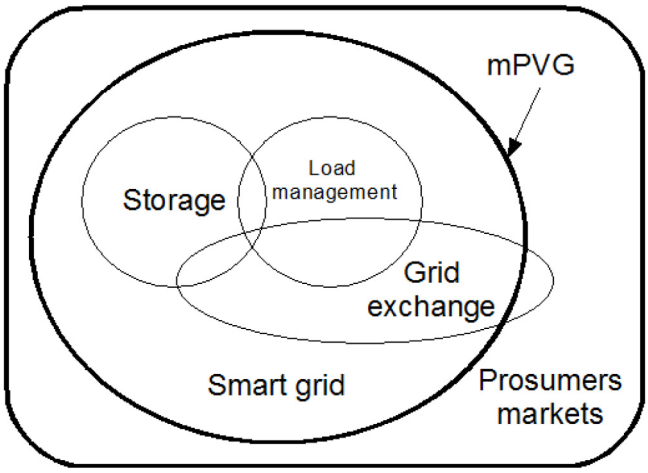

Fig. 1. Components of micro-PV generation.
Source: Own elaboration.

(e.g., for a year). Normally, SSR > 1 because of electricity imports. Reaching satisfactory self-consumption and self-sufficiency rates is an important objective of any prosumer, which requires a fine adjustment of the generation and storage capacities. For example, the SCR of a residential plant with an appropriate storage capacity could reach 65%–75% in Central Europe. This is above the current 30% without battery (CSWD, 2015, p.5). If the battery is combined with a careful load management, SCR will approach 90%. This is a very challenging process because it is subject to many technical and economic requirements. Determining the appropriate PV generation capacity (including panels and inverter) associated to the battery and the auxiliary systems is addressed with optimization and simulation models (see Castillo-Cagigal et al., 2011; Li and Danzer, 2014; Dufo-López, 2015; Erdinc et al., 2015; Ratnam et al., 2015; Khalilpour and Vassallo, 2015 Khalilpour and Vassallo, 2016, p. 41–49 Lauinger et al., 2016; Merei et al., 2016; Opiyo, 2016; Siemer et al., 2016; Quoilin et al., 2016). This complexity is even greater if the site irradiation levels are added to the model. Finally, the profile of electricity demand is not predictable in a perfect manner.

The combination of all these factors explains why researchers have found non-linear relationships between the three key variables (PV plant capacity, battery capacity and the SSR level, see Fig. 2). As it can be observed, the greater the capacity of the PV plant, the greater is the SSR, although this ratio grows at a decreasing rate. Furthermore, if increasing storage capabilities are added to a given level of generation capacity, the SSR also increases. The combination of higher generation and storage capacities tends to a plateau. In other words, each additional generation or storage unit gives rise to a marginally lower increase of SSR value.

The hyperbolic relations found between PV plant size, battery capacity and the self-sufficiency rate have important theoretical implications:

- It is possible to move relatively far beyond the optimum point, without damaging the technical and economic viability of the plant, given the physical requirements and the prices of the equipment.
- The contributions in the literature have found that each prosumer represents a particular case: the relationship between the three considered variables is context-specific. The level of solar irradiation, the demand profile, the differences in the costs of the systems, electricity prices and the possible incentives do not allow to simply extrapolate the values

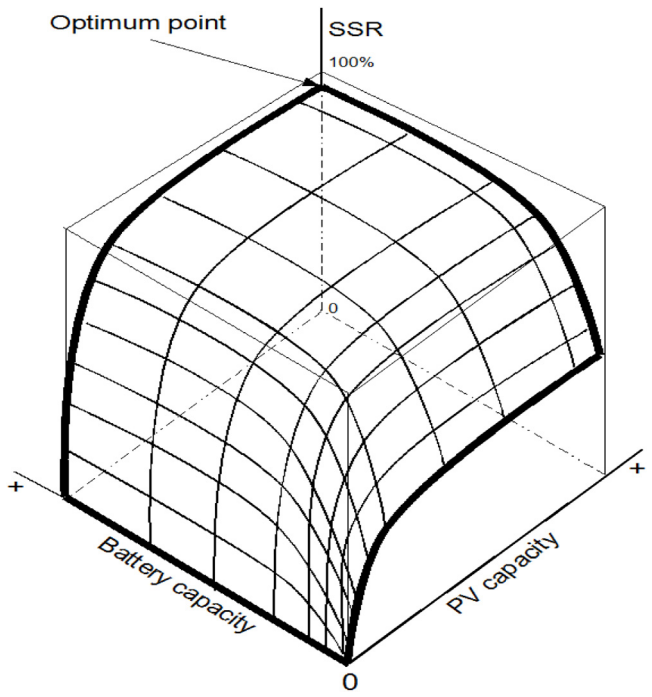

Fig. 2. Hyperbolic relations between PV and battery capacities and the SSR. *Source:* Adapted from Castillo-Cagigal et al. (2011), p. 6–7, Khalilpour and Vassallo (2015), p. 214–215 and Khalilpour and Vassallo (2016), p. 116 and Quoilin et al. (2016), p.64.

from one micro-generator to another (Kazhmiaka et al., 2017).

- The future reduction in the cost of batteries and panels will lead to a more competitive cost of the self-consumed kWh with respect to the retail price. However, this opens the door to excess capacities, especially for the battery, whose frequency of use may drop dramatically (Fitzgerald et al., 2015, p.13). This should not be so surprising: people can also buy cars whose size and horsepower are difficult to justify only on the basis of displacement needs. In this context, the option of "grid departure" gains ground, since the worst contingencies in demand can be solved, especially in sunnier regions. Nonetheless, this option could be stopped if System Operators accept the participation of residential plants in ancillary services and make this participation possible (CEER, 2016, p.7, Green and Staffell, 2017, p. 45–46).

Based on a conceptual framework which considers those relationships, the aim of this paper is to provide a dynamic, easily replicable model of avoided costs which includes the main factors with an influence on those costs, and to apply such model under real-world conditions using data from a residential plant. The paper also aims to identify the impact of regulatory conditions on the economic returns of prosumers with the help of a simulation and different proposed scenarios of the avoided costs. The results highlight the importance of retail prices on the avoided costs and, thus, on the decisions of prosumers to invest in microgeneration. The concept of avoided cost is certainly not new and has been used in the past. However, to the best of our knowledge, it has not been modeled in a dynamic manner, as done in this paper. In addition, the calculation of the influence of different factors has not been carried out in the past. Therefore, this paper covers both research gaps (dynamic modeling of avoided cost and degree of influence of different factors).

Several papers in the literature have analyzed the residential PV prosumage, focusing on different aspects, i.e. analysis of the economic feasibility of residential PV systems with a focus on their profitability (Lara and Santos, 2021; Beraldi et al., 2020; Gbadega and Sun, 2022; Ilham et al., 2022), analysis of the technical design of grid-connected residential PV systems (Argyrou et al., 2021; Hassan, 2022), peer-to-peer energy trading among PV prosumers and consumers (Kanakadhurga and Prabaharan, 2021; Xiong et al., 2022; Gbadega and Sun, 2021b), assessment of the factors influencing the adoption of residential rooftop PV installations (Alrawi et al., 2022) and policy analysis to promote such adoption (Mohan et al., 2022), analysis of the duck curve in PV prosumer installations (Olczak et al., 2021) and demand aggregation of different PV prosumers (Reis et al., 2019). The closest to our paper, but still very different, is (Ellaban and Allasi, 2019). These authors develop an "Integrated Economic Adoption Model" for distributed PV systems, which is made up of four modules: (1) economic assessment of four different proposed electricity retail tariff structures; (2) profitability analysis of those structures; (3) sensitivity analysis of different variables which strongly affect the PV system profitability; and finally, (4) Levelized Cost of Electricity (LCOE) probability distribution based on the Monte Carlo Analysis. The authors argue that the outcome of this model could be useful for household owners, as it would allow them to identify the profitability of the investment under uncertainty. It would also be public-policy relevant, because it would help decision makers to design "retail tariff structure and PV support policies and to conduct economic feasibility analysis for residential and commercial PV projects with different sizes in different locations within their networks" (Ellaban and Allasi, 2019, p.310). However, the model is based on the assumption that the single goal of prosumers is profitability (which we deem too strong an assumption). Furthermore, a dynamic model is not provided, i.e. the model is not forward looking, but only aims to identify in which months the electricity generated by the plant provides a competitive LCOE.

Accordingly, once the literature on the optimization of the size of the plants and auxiliary system for residential installations as well as their main insights have been identified, the next big issue is to assess their results and economic expectations. For this, a dynamic version of the concept of avoided cost is developed. As it is well-known, this is the saving for the prosumer with respect to the situation of a simple consumer, e.g. the difference between the cost of electricity which he consumes from his own plant and the cost he would have incurred if he had bought the electricity from the grid (see below for more details). The avoided cost is a variable which includes important regulatory conditions, which makes it a key element of the payback period and, thus, a key element of the possible renewal of the prosumers' plants.

This paper has three main Sections (2 to 4). In Section 2, the current concept of avoided cost is discussed. Despite its apparent simplicity, important factors are lying behind it which should be carefully addressed. Section 3 develops a dynamic version of the avoided cost concept which is tested using real data from the residential plant. This model is used to simulate the effects of different regulatory frameworks on prosumer investment returns in Section 4. Finally, the paper closes with some conclusions.

2. Background: The avoided cost concept and its complexities

The economic viability of a mPVG plant has to comply with the well-known avoided cost principle: considering the whole lifetime of the plant (T), the generation and storage costs, i.e., the addition of the initial investments and O&M expenditures (C), has to be below the expenditure on the same amount of electricity at retail prices (S) (Hughes, 2005, p.4). The economic balance

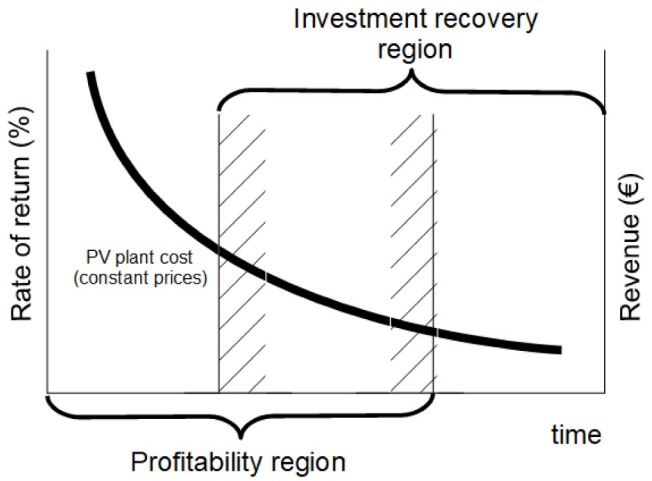

Fig. 3. Profitability versus recovery of PV investments.
Source: Own elaboration.

between exports (imports) to (from) the grid (X–M) should also be taken into account. Therefore,

$$S + (X - M) > C$$

that is,

$$\sum_{1}^{T}\left[q_t p_t^m + \left(X_t p_t^x - M_t p_t^m\right)\right] > a\sum_{1}^{T} q_t$$

where q_t is the annual self-production of electricity, p_t^m and p_t^x are the prices of kWh bought (sold) from (to) the grid, respectively, and a is the cost of generation per kWh.

Three aspects of this expression can be discussed: the assumptions used for the calculation of a, the behavior of the residential plant with respect to the grid and the impact of possible Load Management (L^M) measures.

It is certainly doubtful that residential prosumers invest motivated by the attainment of a given level of profitability. In contrast, their investment decision seems to be related to three aspects: to achieve autonomy with respect to the distribution grid and its problems (Gährs et al., 2015), to gain social prestige (showing environmental awareness, interest for the new technologies, etc.) (Jager, 2006; Nolan et al., 2008; IEA-RETD, 2014, p.29; Korcaj et al., 2015; Trotta, 2018), and to achieve substantial savings with respect to purchases of electricity at retail prices. Whereas commercial plants probably look for short pay-back periods, i.e. a lucrative purpose can be assumed (IEA-RETD, 2016), prosumers probably look for energy at affordable prices, with predictable tariffs and transparent bills, as well as a high-quality service (i.e., absence of flickering or blackouts). The mPVG allows consumers to respond to the frustration for a bad supply service, by changing from the "voice" to the "exit" mode, e.g., abandonment of the grid, according to the classical dichotomy proposed by Hirschman (1972). The reduction in the price of the modules (and auxiliary equipment) has been the main incentive for the gradual change of the economic objectives of the residential mPVG owners, as illustrated in Fig. 3.

As one could logically expect, when the costs of the system were high, the few investors (even residential ones) asked for a given profitability level of the high invested amount. The advantages provided by public support measures contributed to this. When the cost of the modules and the complementary equipment went down significantly, the systems became affordable for many people. Nowadays, the investment costs in an mPVG plant in developed countries are similar to the costs of purchasing a small/medium size car, which turns the plant into a consumer durable good (Nemet, 2019, p.159). Therefore, the recovery of the investment due to the use of the equipment over a long time ends up being more important than the profitability goal.

Table 1
The mPVG with self-sufficiency priority.

PV plant	Flows of electricity	
It is generating	Electricity surplus	Exports to the grid
		To the battery
	No surplus	Instantaneous self-consumption
It is not generating	Battery discharging until its depletion	
	Imports from the grid to be consumed	

When the goal is to capitalize the investment (I), the annuity per kWh is given by the following expression,

$$I\frac{i(1+i)^T}{(1+i)^T - 1} \tag{1}$$

where i is the interest rate and T refers to the useful lifetime of the plant. When the goal is simply to recover the initial investment, the annuity is

$$\frac{I}{T} \tag{2}$$

The difference between both values can be considerable. For example, in the case of the real plant used in this paper as a reference for the simulations (see below and Appendix A), (1) becomes €1233/year whereas (2) is €566/year for an initial investment of €16,980, an interest rate of 6% and a $T = 30$ years.

After calculating the annuity, the cost of generation per kWh (a) can be obtained. In order to do so, such annuity has to be multiplied by T (30 years) and the accumulated amount of O&M costs (m_t) has to be added (in our real-world case, this is €1,076 = €2.99/month·360 months). This amount is then divided by the total amount of kWh generated during the whole useful lifetime of the plant. In our example, this estimated amount is 249,919 kWh, having considered an annual degradation rate of the generation capacity of modules of 0.74%. With these numbers, $a = 0.0722$€/kWh, whereas the generation cost when the aim is to capitalize the investment according to Staffell et al. (2015), i.e. making a profit out of it, is 0.1523€/kWh.

The second factor to be considered is that the economic behavior of prosumers with respect to the grid will probably be focused on the self-sufficiency priority. This goal implies residual exports. Therefore, the following aspects should be considered:

- When the PV plant is not generating and the battery is empty, all the consumed electricity comes from the grid.
- When the PV plant generates electricity, this one is instantaneously consumed in case of no surplus. However, in case of an electricity excess, the battery is fully charged and, then, energy is exported.

These rules are shown in Table 1. With respect to the common pattern, it can be expected that there are smaller surpluses in mild winters, although the electricity consumption of the home, especially during sunset, is higher, which requires the use of the stored energy. In contrast, production grows in the summer and once the high consumption of air-conditioning devices has been met, the surpluses can be stored and, eventually, sold. In the model which is proposed in this paper, it is assumed that the exports (the final destiny of the kWh which cannot be consumed instantly or stored) are residual.

The priority of self-consumption may lead to a greater electricity consumption. This is not a mere shift of consumption (a well-proven fact), but a more frequent use of some home appliances. Beyond the concentration of their activity in the hours with a greater level of generation (and even beyond if batteries are available), the prosumer, who aims to reach a given level of SSR, increases his electricity consumption with respect to a previous situation. In the future, with the support of smart devices which can control home appliances, the accumulated experience will allow the prosumer to reduce his surplus. He can use the home appliances more intensively or buy new ones. This leads to greater levels of comfort and accelerates the recovery of the investment in the plant. More specifically, two kinds of consumer loads should be distinguished (Zipperer et al., 2013; Longe et al., 2017, p.4): (1) Non-shiftable appliances (or non-schedulable devices) such as lighting, cooking systems or TV sets; (2) Shiftable appliances.

Instead of exporting electricity surpluses in order to contribute to the recovery of the investment, because their low currently prices discourage them, the prosumer chooses to increase the level and/or frequency of use of shiftable appliances. These are the only devices whose operation can be adjusted at will:

• As a result of an intensification of device operation, for example, the air conditioning system is set at a lower temperature, which leads to an increase in its consumption. Formally, $\psi^k \cdot \sigma^k$, $\psi^k > 1$ considering, on the one hand, that the activation time, $\tau = [t^*, t^{**}]$, of the k home appliance did not change and, on the other hand, that its energy demand is given by,

$$x^k = \sum_{t^*}^{t^{**}} \sigma_t^k$$

where σ^k is its previous consumption.

The appliance time of use is extended: $\tau^* > \tau$, with τ being the previous time of use. For example, the air conditioning system works more time than it was usual.

Therefore, assuming that the electricity imports do not rise as a result of these load management measures and other new devices aren't added to the household endowment, the economic impact of the load management is given by the expression

$$L^M = p_t^m \sum_k \left[\sum_\tau \psi^k \sigma_t^k + \sum_{\tau^*} \sigma_t^k \right]$$

This expression represents the value of the extra electricity self-consumed at retail import prices. The aim is to mitigate the daily PV generation peaks which increase the self-consumption ratio and reduce exports (and probably imports).

Therefore, the prosumer has two options when changing his condition from a simple consumer to a prosumer:

- He can take the previous levels of electricity consumption as a reference in order to install a level of capacity whose generation peaks are close to consumption peaks.
- He can install a capacity which ensures a comparative increase in electricity consumption through a more intensive/frequent use of shiftable appliances. And, perhaps, he might expect to buy other equipment, such as an electric car. In fact, in line with the avoided cost criterion, the more the own-generated electricity he consumes, the faster the investment is recovered (see below).

Furthermore, in both cases, we have to consider the possibility that the new prosumer adopts efficiency and energy savings measures, such as the installation of LEDs, improvements in the insulation of his home, the replacement of some home appliances, etc. Making use of the self-generated electricity provides a considerable incentive in this regard.

If the capacity of the mPVG plant is adjusted according to the expectation of a higher electricity consumption, an increase in welfare is achieved without additional detrimental effects on the environment. However, this decision may lead to a rebound effect (Sorrell and Dimitropoulos, 2007; Seebauer, 2018). The improvement in the efficiency of the equipment goes together with the need to maintain a high level of self-consumption. Therefore, this fact does not entail any detrimental economic effect for the prosumer.

A final point is worth making: the increase in self-consumption and the concomitant reduction in exports (and imports) do not only depend on the measures of load management that the prosumer may adopt, but also on pure chance. In this context, the weather can play a relevant role. For example, in places with a Mediterranean climate, PV generation in a cloudy day can be as much as 10 times lower than in a sunny day. Then, if the goal is to reduce imports, the prosumer can only wait. He has some margin of maneouvre if he has a battery, although the recharging process is very slow in cloudy days. If no one is at home, the scarce consumption may be covered with the limited level of self-generation.

The analysis of load management, that is, the set of behavioral measures and electricity devices which deal with load management, is subtle and complex. Unfortunately, data on the behavioral changes in electricity consumption due to the installation of an mPVG plant are not available. Therefore, the previous situation of the prosumer is ignored in the following pages and it is assumed that the plant meets his consumption expectations and that he tries to use the electricity he generates to the maximum extent possible, which reduces exports (and, then, imports).

3. Methods. A dynamic model of the avoided cost: Design and application

Given an O&M cost and a level of annual level of generation which are constant during the whole lifetime of the mPVG plant, the cost per kWh generated is:

$$a = \frac{I + \overline{m}T}{\overline{q}T}$$

Therefore, the dynamic expression of such cost is:

$$a = \frac{I + \overline{m} \cdot T}{\sum_0^T q_0 \cdot e^{-\alpha t}}$$

Taking into account the following considerations:

- The annual generation (q_t) is expressed in terms of the production in the first year (q_0), that is, $q_t = q_0 . e^{-\alpha t}$, with $\alpha = 0.74\%$. This figure has already been used before because it is the most commonly accepted degradation rate of the modules (Mir-Artigues and del Río, 2016, p. 19–20).
- For reasons of simplicity, the O&M cost is assumed constant for all the years being considered.
- T refers to the useful lifetime of the plant which, as suggested before, is conventionally set at around 30 years.
- According to the above explanation, the prosumer only recovers the value of the investment, but does not try to capitalize it (i.e., he does not try to make a profit).
- In order to facilitate the calculation, and given the relatively modest cost of a residential plant, the investment is assumed to be paid in cash.
- The plant is aimed at self-consumption and, thus, exports are marginal. This assumption requires that the simulations are made with a plant which meets this criterion.

- Load management is not explicitly included in the model. It is assumed that the prosumer takes the appropriate measures to save energy and, simultaneously, he uses the self-generated electricity to the maximum extent possible.

On the other hand, the value of the annual flow of exports is:

$$X_0 \cdot e^{-\alpha t} \cdot p_0^x \cdot e^{-\beta t} = X_0 \cdot p_0^x \cdot e^{-(\alpha+\beta)t}$$

where p_0^x refers to the initial annual (or monthly) price and X_0 is the annual (or monthly) quantity of exports. It is assumed that the possibility to export is being lost with the aging of the modules (factor α) and the reduction in the export prices (factor β). In contrast, the imports from the grid can be expressed as

$$M_0 \cdot p_0^m \cdot e^{(\alpha+\gamma)t}$$

since the imports grow over time at a rate of α, and the price paid per kWh (or retail electricity price, including all taxes) grows at a rate of γ.

The current value of the *avoided cost* in the case of a plant whose initial investment has been I, that is, $V_0(I)$, is equal to the following expression:

$$V_0(I) = \frac{1}{(1+i)^T} \sum_0^T q_0 \cdot p_0^m \cdot e^{(\gamma-\alpha)t} + X_0 \cdot p_0^x \cdot e^{-(\alpha+\beta)t} - a \cdot q_0 \cdot e^{-\alpha t}$$

This expression assesses the self-generated kWh per unit of time (whether for instantaneous consumption or for the storage or sale to the grid) at the retail electricity price (or import price p_0^m), taking into account its dynamics, minus the generation cost, where a is a given value. The possible revenues from the exported kWh are added. As it can be observed, the same annual discount rate i has been assumed for the whole period T. In the case of exports, probably $p^x < p^m$ and, thus, such revenue entails only a small reduction of the generation costs of those kWh. Rearranging the terms and setting $X_0 = \varphi q_0$, $0 < \varphi < 1$, and $p_0^x = \mu p_0^m$, $0 < \mu < 1$, the following expression is obtained

$$V_0(I) = \frac{1}{(1+i)^T} \sum_0^T q_0 e^{-\alpha t} \left[p_0^m \left(e^{\gamma t} + \varphi\mu e^{-\beta t} \right) - a \right]$$

or, also:

$$V_0(I) = \frac{q_0}{(1+i)^T} \left[p_0^m \sum_0^T e^{-\alpha t} e^{\gamma t} + \varphi\mu p_0^m \sum_0^T e^{-\alpha t} e^{-\beta t} - a \sum_0^T e^{-\alpha t} \right] \quad (3)$$

This equation allows us to obtain different hypothetical trends of the avoided cost for real mPVG plants, as well as to carry out simulations according to given requirements. The data used in these pages come from a residential plant whose technical and economic features are provided in Appendix A. All the simulations and scenarios in the following paragraphs come from real data for 2019. More specifically, Table 2 shows the values of the parameters and the assumptions on the variables in expression (3) for the plant being considered.

In such expression (3) and in Table 2, there isn't a reference to possible changes in the contractual conditions for the prosumer after the installation of the PV modules. For example, the prosumer may decide to reduce the capacity contracted with the grid, a measure which has an obvious economic impact on two-part tariff systems. If Θ is the difference between the contracted capacity before and after the installation of the plant, v_0 is the initial fee for the power term (€/kW) and ξ is its expected evolution over time, then expression (3) should be rewritten as follows:

$$V_0(I) + \frac{\Theta v_0}{(1+i)^T} \sum_0^T e^{\xi t}$$

This includes the current value of the avoided cost plus the flow of savings due to the reduction of the payment for the power term. This means that the calculations carried out in these pages do not necessarily reflect the reduction of the electricity bill achieved by the prosumer. In cases such as the Spanish one, where the connection fees are high due to the so-called tariff deficit (see, e.g., Del Río and Mir-Artigues, 2012, 2014), the trend of the avoided cost could be significantly improved if the capacity contracted was reduced. Since this issue cannot be generalized, it has been decided to omit it.

Fig. 4 shows the evolution of the accumulated avoided cost for the 30 years of useful lifetime of the plant used as reference for the empirical analysis, according to the data and assumptions included in Table 2. As it can be observed, the avoided cost covers the initial investment of 13.7 years.

Since expression (3) contains several factors, it is highly relevant to identify the contribution of each of them (parameter and variable) to the avoided cost. Thus, the first step is to express the geometrical sums in expression (3) in the following manner:

$$p_0^m \frac{1 - e^{(\gamma+\alpha)(T+1)}}{1 - e^{(\gamma+\alpha)}} + \varphi\mu p_0^m \frac{1 - e^{-(\alpha+\beta)(T+1)}}{1 - e^{-(\alpha+\beta)}} - a \frac{1 - e^{-\alpha(T+1)}}{1 - e^{-\alpha}}$$

After multiplying by the factor $\frac{q_0}{(1+i)^T}$, a version of equation (3) is obtained and the following partial derivatives are calculated:

$$\frac{\partial V_0(I)}{\partial \varphi} = p_0^m \mu \frac{1 - e^{-(\alpha+\beta)(T+1)}}{1 - e^{-(\alpha+\beta)}}$$

$$\frac{\partial V_0(I)}{\partial \mu} = p_0^m \varphi \frac{1 - e^{-(\alpha+\beta)(T+1)}}{1 - e^{-(\alpha+\beta)}}$$

$$\frac{\partial V_0(I)}{\partial \beta} = p_0^m \varphi\mu e^{-(\alpha+\beta)} \frac{(T+1)\, e^{-(\alpha+\beta)T} - T e^{-(\alpha+\beta)(T+1)} - 1}{\left[1 - e^{-(\alpha+\beta)}\right]^2}$$

$$\frac{\partial V_0(I)}{\partial \gamma} = p_0^m e^{(\gamma-\alpha)} \frac{-(T+1)\, e^{(\gamma-\alpha)T} + T e^{(\gamma-\alpha)(T+1)} + 1}{\left[1 - e^{(\gamma-\alpha)}\right]^2}$$

If p_0^m, T and α are substituted in these expressions and the corresponding calculations are carried out, then the total differential of V_0 is obtained:

$$dV_0(I) = 1.5833 d\varphi + 1.5992 d\mu - 4.7125 d\beta + 130.245 d\gamma$$

In other words:

- A one-unit increase in φ, which represents the share of the self-generated electricity which is exported, leads to an increase of 1.5833 units of the avoided cost, $V_0(I)$.
- A one-unit increase in μ, which refers to the share of the initial export price, leads to an increase of 1.5992 units of $V_0(I)$.
- A one-unit increase in β, which represents the dynamics of export prices, leads to a reduction of 4.7125 units in $V_0(I)$.
- A one-unit increase in γ, which shows the evolution of the import prices, leads to an increase of 130.245 units in $V_0(I)$.

This result shows the importance of the weight and the evolution of the retail electricity price on the avoided cost: its impact is much higher than the rest of factors and, the faster it grows, the greater the savings for prosumers. This is arguably the most relevant result of this paper.

Table 2
Parameters and variables from the real PV plant.

Parameters/Variables	Value	Comments
q_o	9,258.786 kWh	This is the value in the first operational year of the plant.
p_0^m	0.266€/kWh	Average retail electricity price, fees and taxes included.
X_0	1,861.599 kWh	Amount sold to the grid in 2019.
I	2%/yearly	By assumption.
T	30 years	Generally accepted value.
A	0.0722€/kWh	Initial investment (16,980€) plus O&M cost (1,076.4€) divided by the total amount of kWh generated (249,919.03 kWh).
φ	0.201	In 2019 "La Torreta" plant generated 9,258.786 kWh and exported 1,861.599 kWh.
μ	0.199	In 2019, the average retail electricity price was 0.266€/kWh and the feed-in price for prosumers was 0.053€/kWh.
α	−0.74%	Generally accepted value.
β	−0.5%/annual	By assumption, export electricity prices diminish at a 0.5%/annual rate[a].
γ	+2%/annual	By assumption, import or retail prices grow at a 2% annual rate (according to IEA, 2016, p.41)[a]

[a]The difference between the growth rates of export and import electricity prices is due to the assumption that the government uses this instrument in order to encourage self-consumption (indeed, self-sufficiency) and discourage exports.

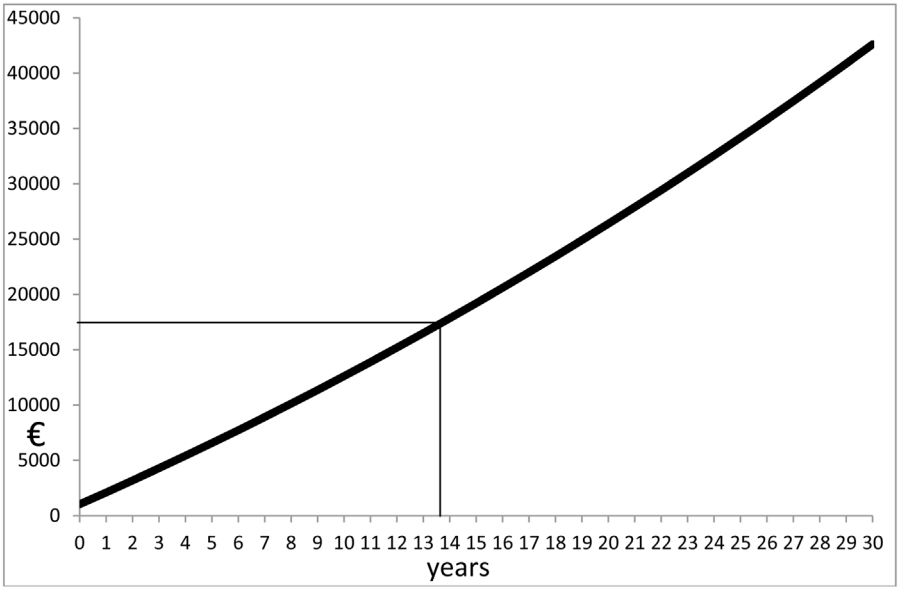

Fig. 4. The accumulated avoided cost according to the initial assumptions.

On the basis of the results obtained in the previous paragraphs, when the cumulated avoided cost equals the initial investment, the existing installation may be replaced. A first approach to this issue comes from Fig. 5.

In point *A*, the accumulated *avoided cost* of the initial plant equals the value of the initial investment *I*. In this moment t^*, the decreasing trend of the investment cost for new plants (that is, the reduction in the manufacturing cost of the modules and complementary equipment and the soft cost) has reached the value represented by point *B*. This entails a shift from I to I^* according to expression $I = (1+\rho) \cdot I^*$, $\rho > 0$. Therefore, the replacement of the plant can occur at any time within the interval $[t^*, T^*]$, that is, after the avoided cost reaches the value of the initial investment and until the lifetime of the initial plant ends. Therefore, a first analysis of the substitution process of residential plants can be carried out under the following assumptions:

- The residual value of the replaced plant is ignored. IRENA (2019), p.50 suggests that the price of a used module which is in good condition may reach 70% of its initial price.
- The substitution does not change the installed capacity, i.e., there isn't more space in the roof and/or it is not possible to increase it due to regulatory restrictions.
- The regulatory conditions are assumed to persist and, thus, the parameters and variables of the avoided cost expression are not modified.

Therefore, the following expression can be written:

$$V_0\left(I^*\right) = \frac{1}{(1+i)^T} \sum_{t^*}^{T^{**}} q_0 e^{-\alpha t} \left[p_0^m \left(e^{\gamma t} + \varphi \mu e^{-\beta t} \right) - \frac{a}{(1+\delta)} \right]$$

with $\delta > 0$. This expression indicates that the new plant has the expectation of a higher net avoided cost. In fact, the investment will be recovered ahead of time since the generation costs due to the improvements in the manufacturing and installation of the modules and auxiliary systems are lower now. More specifically, on the basis of the information provided in Appendix A, the total investment in point B of Fig. 5 is €8177.08 (and, thus, $\rho = 1.07$)

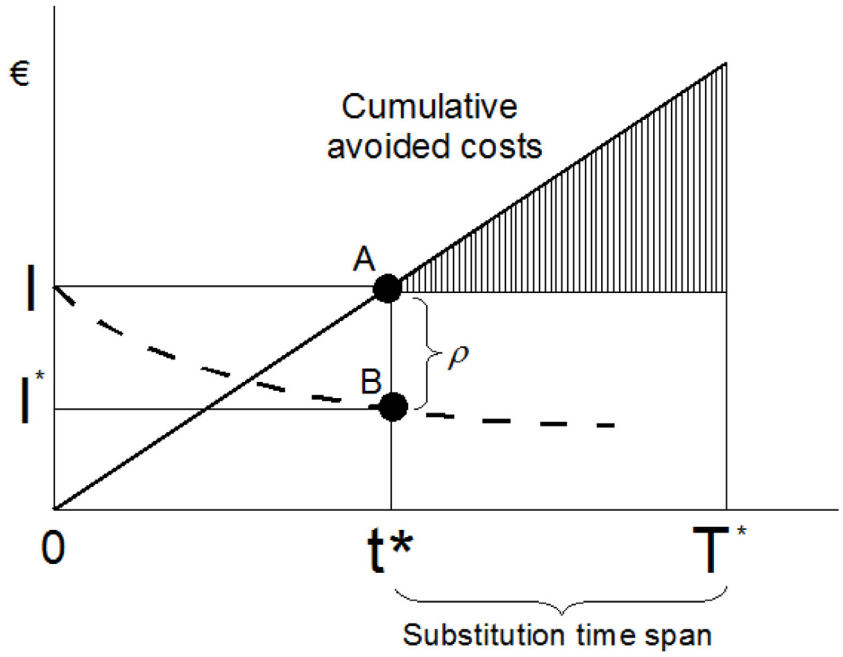

Fig. 5. Substitution of mPVG plants.

Table 3
Types of mPVG regulation.
Source: Own elaboration from IEA (2016, 2018), Green (2019), EC (2017), IRENA (2019a), Ramalho et al. (2017), Poullikkas et al. (2013).

Priority	Exports and import prices	Some examples
Self-consumption	$p^m \sim p^x$	Belgium, Brazil, some Canada provinces, Finland, Israel, The Netherlands, United Kingdom, some states in US
	$p^m >> p^x$	Chile, China, Denmark, Italy, Portugal, Spain, Switzerland
To feed the grid	Feed-in tariff (FiT)	France, Germany, Japan

and, if the O&M costs and T do not change, the generation cost goes down to 0.037€/kWh. Therefore, $\delta = 1.95$.

4. Results: Impacts of the regulatory framework

The dynamic version of the avoided cost allows us to refine the impact of the regulatory framework on the economic results obtained by the prosumer. According to the literature, Table 3 shows the main regulatory types of residential generation.

As it is well-known, there is a wide diversity of regulatory frameworks, with many details which distinguish them from one another. Therefore, Table 3 only suggests a classification which takes into account the remuneration of the surplus kWh which the prosumer feeds to the grid, with respect to the price per kWh paid as a consumer.

There are two main approaches: to promote residential generation with the aim to feed the grid or to favor self-consumption. In the first case, the regulation tends to set preferential prices (or feed-in tariffs, FITs), which are usually above the retail prices (otherwise, it would not make sense to export) and ensure a certain level of revenues for the prosumer. When self-consumption is the priority, some regulations opt for the so-called net metering, that is, the kWh exported to the grid is remunerated at a price which is close to the retail electricity price. Net metering strictly means compensation in physical terms. Therefore, the term "net billing" is more appropriate in this context (see Mir-Artigues and del Río, 2016, p. 245). Other countries remunerate the exports with a price which is much lower than the retail price. In some cases, such price can be zero, although the dominant approach is to remunerate the surplus of prosumers according to the price of the wholesale electricity market. Given that it is likely that those prices will be below the generation cost, some regulations add a bonus. These alternatives usually go together with the following regulatory elements:

- The compensation period set in the regulation: the shorter it is, the less beneficial for the prosumer it is.
- The share of fees and taxes in the retail electricity prices and how these prices are reflected in the exchanges of the prosumers with the grid.

Most regulations do not support the purchase of equipment. The spectacular reduction in the costs and prices of modules and other auxiliary systems justifies this, although batteries are a different story. For a residential installation $\leq$5 kW, the battery may represent more than half of the total investment and, for an installation with a greater capacity, it can be about a third of the total investment, as it is the case considered in this paper. Given that the battery would increase the level of self-consumption, support for the purchase of storage systems should be generalized. As commented below, it is not only an issue of providing an economic incentive, but rather one of creating a psychological frame which encourages the purchase of residential systems.

Given this information, and taking the plant considered as a reference, four scenarios are proposed in Table 4. Both the Net Metering (NM) policy as well as the No Exports Compensation (NEC) policy include two hypothetical scenarios, called Best and Worst, depending on their impact on the interests of prosumers. The four scenarios are based on the assumption that the same share of the electricity generated is exported (parameter φ). This connection between exports and generation ensures that the exchanges with the grid are affected by the degradation of the modules. A first difference between the scenarios is the existence

Table 4
Parameters and variables under the two policies and four scenarios.

Parameters/variables	Net metering		No exports compensation	
	Best	Worst	Best	Worst
Battery subsidy	50%	0%	50%	0%
φ	0.201	0.201	0.201	0.201
μ	0.6	0.6	0	0
β	5%	1%	0	0
γ	5%	1%	5%	1%

Table 5
Main results in the different scenarios.

Scenarios	Recovery time (years)	Maximum value (€)
Net metering (Best)	8.5	79,718.3
Net metering (Worst)	13.4	37,532.5
No economic compensation (Best)	9.1	77,274.8
No economic compensation (Worst)	15.3	33,567.5

or absence of subsidies for batteries. When these subsidies are provided, it has been assumed that they represent about 50% of the purchase price.

According to the data of our real plant, the investment of €16,980 is reduced to €13,880 when the purchase of the battery is subsidized with €3,100. The cost of the kWh generated would go down from 0.07225€/kWh to 0.05984€/kWh, which entails a reduction of 17.17%. As mentioned above, the parameter μ indicates the relationship between the export and retail prices: its value is relatively high under a NM regulation and zero under a NEC policy. Under a NM regulation, the export price represents 60% of the retail price, which includes the taxes borne by the consumer. According to EC (2019, p.2), 40% is the EU average percentage of those components in the retail price paid by small consumers. Under a NEC policy, the electricity sold to the grid does not receive any compensation. On the other hand, the parameter β (which refers to the dynamics of export prices) takes positive values in the case of NM, with an annual increase of 5% in the best case (e.g., they increase to the same extent as the retail prices) and 1% in the worst case (a lower increase, albeit a positive one, given that the character of the NM policy cannot be changed). Of course, such parameter is null under a NEC regulation. Finally, the evolution of import prices (parameter γ) is the same for both policies, although it increases by an annual 5% in the best case for the prosumer and by 1% in the worst case. The reduction or freezing of the retail prices has not been taken into account. Although experts on the topic do not assume so, any type of trend is possible in the future. However, it is not the purpose of the current simulation to speculate on this.

Fig. 6 shows the accumulated trends in the avoided cost for the 4 scenarios, whereas Table 5 shows the period over which the investment is recovered, as well as the total accumulated sum of the avoided cost in the simulations.

As it can be observed, the best case and worst case scenarios are far away from each other, whereas the NM and NEC curves are close to each other. This result confirms the important impact of the retail prices on the avoided cost. Neither the existence of subsidies, nor the remuneration conditions of the surplus make a big difference for the prosumer. In contrast, when the hypothetical increasing trend of retail prices is significantly slowed, the total volume being saved is substantially reduced (by around a half, under the assumptions used in the simulation).

Although this result reduces the impact of regulatory conditions (subsidies and grid exchanges), it does not mean that those conditions are not relevant at all. On the one hand, from a strictly economic perspective, a subsidy reduces the necessary initial investment and, thus, the recovery period (between 35% and 40%). A high remuneration of the surplus would have the same effect although, to the best of our knowledge, this approach has not been followed by any country. On the other hand, there is no doubt that the possibility to accelerate the recovery of the investment has a large psychological impact on the future prosumer.

Some authors, using a conceptual framework based on Behavioral Economics, have analyzed the discount rates that people apply in their daily decisions. In the case of the purchase of more efficient durable consumer goods (washing machines, refrigerators etc.), it has been observed that their higher price discourages their purchase (Prelec and Loewenstein, 1997; Loewenstein, 2009; Neij et al., 2009), despite the small but constant flow of future savings, which offsets such higher price. A higher accumulated value becomes less relevant than the present preferences, which magnifies the value of the initial investment. Therefore, some governments have provided subsidies to the purchase of those goods. Despite the lack of studies, the same approach could be applied to the installation of residential PV plants: without prejudging the degree of environmental awareness of the prosumers, the fact is that the relatively high initial investment of the plant dwarfs the reduction of the electricity bill (which generally represents a small share of the household income) which takes place over many years. In this context, direct incentives such as subsidies for the purchase of batteries could be very useful to encourage citizens to install an mPVG plant. For the reasons mentioned above, these subsidies could provide an even greater incentive than the increase in the remuneration of the surplus. They would shorten the period over which the investment is recovered and would mitigate the aforementioned barrier on the preference for the present, i.e., they would offset the effects of the relatively high discount rates applied by the potential prosumers when buying an mPVG plant.

5. Conclusions and policy implications

This article shows that the evolution of the retail prices has a major influence on the avoided cost, which is a key variable when assessing the economic results of prosumers under self-consumption. It is necessary to include all the price components in the model, i.e., the cost of kWh plus all the fees and taxes. From an avoided cost perspective, the only thing that matters is the savings with respect to retail prices. This relevance of retail prices is behind the investment decisions of residential plants. On the one hand, it gives those investments an inherent uncertain character, since their economic feasibility depends on an unknown factor which extends into a distant future. The dynamics of retail electricity prices is unknown beyond the next few years. This uncertainty aggravates an investment decision which collides with the psychological preference for the present.

Therefore, there is a very important role to be played by regulation: it can encourage the investment by reducing the recovery period. If the accumulated avoided cost equals the initial investment earlier, this reduces both the uncertainty (the period is shorter) and the psychological impact of a strong initial expense.

In terms of the avoided cost, subsidies to the initial investment (particularly regarding the battery) do not significantly alter the relevance of the evolution of retail prices. However, they change the psychological perception of the economic operation, probably more than the remuneration of the surplus fed into the grid and other measures.

The dynamic expression of the avoided cost does not include physical restrictions (amount, time schedule) or extra fees for prosumers. It is highly likely that, for residential plants for

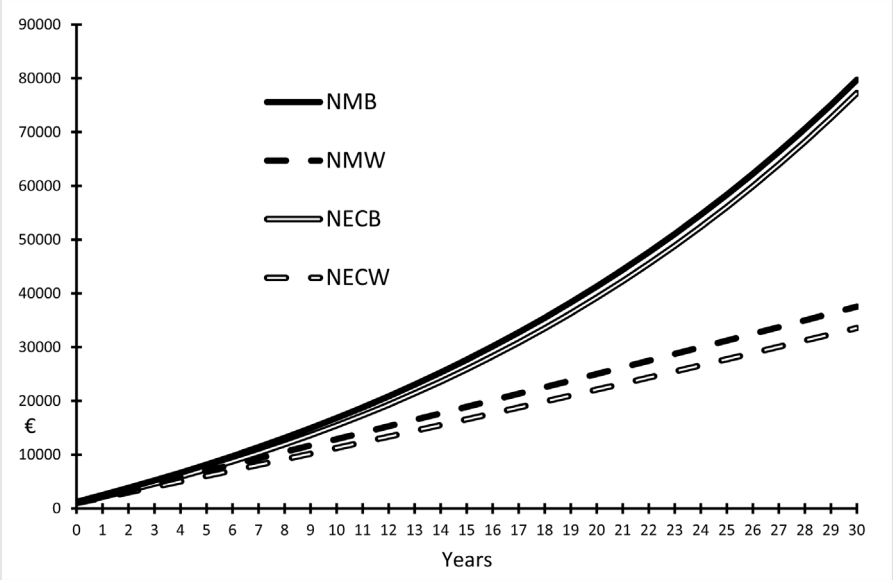

Fig. 6. Four scenarios on the avoided cost.

self-consumption, those requirements on exports do not have a meaningful economic impact. However, they may have a detrimental psychological influence. Thus, they should be avoided, if the aim is to encourage mPVG.

From a methodological point of view, the mathematical expressions developed in this paper contain the main factors which influence the avoided cost and they are relatively simple. They can easily be applied to any regulatory context and can also be adjusted to the expected evolution of retail prices. Therefore, the model developed in this paper can be easily implemented in any context and can be appropriately modified in order to add the requirements set in regulations. In this sense, the model allows carrying out an initial assessment of different regulatory scenarios.

Future investigations should focus on the impact of load management on the avoided cost, including changes in the patterns and levels of electricity consumption of the prosumers and comparing the periods both before and after the residential plant as well as during its operation. In general, the model can be refined in the future by including more determinants, although the empirical analysis will be subject to the availability of data.

Despite the flexibility of the proposed model, which should be considered as a general framework for the analysis of avoided costs, its real-world application is limited by the following two aspects, which suggest further avenues for future research:

- Retail electricity prices usually change in the short term. Thus, in case the regulatory framework allowed the recovery of the investment made by the prosumer in a few years, it would be justified to include some hypotheses on the evolution of electricity retail prices in the medium term in the model. This would lead to several scenarios, which should also contain hypotheses about the price for renewing the PV equipment, particularly the inverter and the battery.
- The impact of load management on the avoided cost should be added to the model. This would include changes in the patterns and levels of electricity consumption of the prosumers and comparing the periods both before and after the residential plant as well as during its operation. The inclusion of the load management factor is particularly difficult since its influence is contingent upon the household structure and the life style of the residents. As of now, there aren't sufficient statistical data in order to create a prosumers typology on the basis of which they can manage their own electricity consumption. That is, they aim to adjust their consumption to the generation profile every day, given the geographical location of the plant and the existing regulatory framework.

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.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank the owner of "La Torreta" plant for providing investment and operation data for such installation.

Appendix A. Data and assumptions

The following table shows the data on the investment costs of "La Torreta" plant located near Lleida (Catalonia, Spain). (see Table A.1).

The plant has a size of 10.8 kWp, it is installed in the roof with a direction of 180° and an inclination of 10°. The house has electric heating (heat bomb) and a charging point for an electric vehicle (medium size). The lifetime of the module is estimated in 30 years and battery lifetime is 15 years. The O&M outlays are 2.99€/month. The module manufacturer guarantees 99% of the design power the first year and a linear loss for the remaining 29 years until 80% of the initial performance is reached. Therefore, the generation capacity goes down at 0.74% annual cumulative rate.

The plant started its activity at the end of 2018. Therefore, 2019 is the first year of actual operation. Table A.2 shows the data on the main monthly generation, consumption, self-consumption, exports and imports:

Table A.1
Main data.
Source: Data provided by the owner of the plant (rounded figures).

Investment	Value (€)
Mono-crystalline modules	3,780
Inverter	1,100
Support structures	800
Electric material and installation works	4,600
Battery (9 kW)	6,200
Soft costs (tax added)	500
Total	16,980

Grid electricity prices paid by final consumers for 2019, all items included (energy, fees and taxes), are shown in Table A.3.

In the Spanish electricity system, the consumer price is around 0.14€/kWh. The PV generation cost is around 0.08–0.1€/kWh which, with battery, increases to 0.16–0.18€/kWh. This excludes any remuneration due to exports.

With respect to the price of modules, we used the quarterly data $/W for the years 2008–2019 from IRENA (2016) and IRENA (2019), p. 27–29 and IRENA (2020), p. 61–66 and Green (2019). These figures were then converted into average annual values. In order to extrapolate the prices up to 2041, an exponential curve was fitted, whose expression was $\$/W = 5.43t - 1.166$, with an $R^2 = 0.9338$. With this, the US $3.82/W of Q1 2008 went down to US $0.071/W as the average value for 2041. The figures obtained were transformed into indexes (2008 = 100). For the year 2019, the index had gone down to 5.517 and, for 2048, it had decreased to 1.317. Therefore, the amount of €3,780 for the purchase of the modules of the "La Torreta" plant, between the year 14 and 15, has been estimated at €3140, a number which went down to €902 for 2048. For the rest of equipment and soft costs, an annual reduction of 5% in their price was assumed. With this, the initial investment of €16,980 in 2019, after 14.5 years of operation, went down for a new plant to €8,177. And, for 2048, the total cost of the installation was $/kW360, a central value with respect to IRENA (IRENA, 2019a, p. 27–29), which estimates $/kW165–$/kW481. The annuity per kWh for the recovery of this new investment was 0.109€/kWh, assuming the same total generation than the initial plant and $T = 30$ years.

Appendix B. Self-consumption and the rebound effect

There is no reason to think that the plant which is installed by a prosumer will have a capacity which is adapted to his previous electricity consumption. Assuming that sufficient space to capture solar irradiation is available, the new prosumer may opt for a capacity which allows him to consume more electricity or use air conditioning devices, washing machines or dishwashers more frequently or intensively. He may even buy new electric equipment. It is assumed that he would not sell his surplus to the grid, since the aim is to achieve a high value of the SSR. In this case, the load management serves a greater level of electricity consumption, although a self-generated one.

As it is well known, investments in more efficient systems may lead to a rebound effect, i.e., the recently bought appliance will lead to a greater use overtime (without affecting the quality of service), which implies energy savings lower than those expected. For example, energy-efficient light bulbs are installed but they are switched on for a longer time, or the thermostat of the heating system is set at a higher level than before. Fig. B.1 shows the different possibilities, using the point σ_0, which indicates the current efficiency level, as a reference. Therefore, a new appliance could have this level or an improved one. Moreover, the figure has been built based on the assumption that the price of the most efficient appliance is not a barrier to its purchase and that the price of electricity is outside the considered circumstances. In addition, the analysis is only related to the limits of the home, i.e., only direct effects are considered.

The pursuit of a higher SSR combined with more efficient appliances leads to the following situations:

- The consumer decides to reduce the use of a given appliance (and, thus, electricity demand) either due to volunteerism (perhaps motivated by environmental awareness) or need (absence of economic resources).
- A new appliance has an improved efficiency, so the reduction in energy consumption would be the one indicated by the expected effect. However, an increase in its use partially offsets the potential savings due to efficiency. This is the rebound effect.
- In case of a prosumer plant, the self-sufficiency goal can lead to an increase in electricity consumption. In some cases, a backfire effect is possible: it occurs when the increased use of a more efficient device grows to such extent that it totally offsets the efficiency improvement.

The last two situations can be the result of measures to adjust the domestic demand to the electricity generated.

If an appliance is replaced by a more efficient one, that is, with a consumption of $\lambda\sigma$, $0 < \lambda < 1$, the final electricity saving s_t^k, is equal to

$$s_t^k = \sum_{\tau} p_t^m (1-\lambda)\, \sigma_t^k - \sum_{\tau^*} p_t^m \lambda \sigma_t^k$$

Table A.2
Performance data for 2019.

kWh	Generation	Consumption	Self-consumption	Exports	Imports
January	425.940	1,106.907	392.052	33.888	714.855
February	566.208	521.714	483.755	82.453	37.959
March	902.109	774.352	735.245	166.864	39.107
April	903.381	721.223	710.415	192.966	10.808
May	915.582	617.622	606.820	308.762	10.802
June	999.371	730.290	688.902	310.469	41.388
July	1,209.978	1,025.475	978.117	231.861	47.358
August	960.393	764.880	722.738	237.655	42.142
September	829.141	722.652	649.296	179.845	73.356
October	730.520	759.432	654.479	76.041	104.953
November	522.680	766.677	490.625	32.055	276.052
December	293.483	864.069	284.743	8.740	579.326
Total	9,258.786	9,375.293	7,397.187	1,861.599	1,978.106

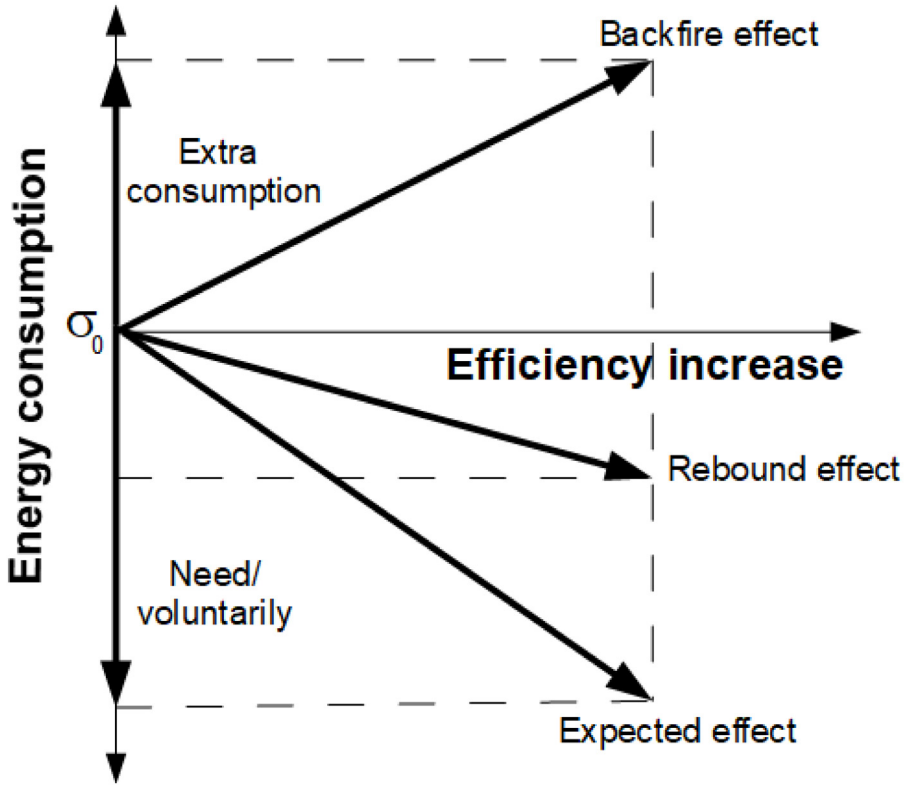

Fig. B.1. Forms of the rebound effect.
Source: Own elaboration.

Table A.3
Retail prices 2019.

Prices	€/kWh[a]
January–February	0.268
March–April	0.279
May–June	0.276
July–August	0.253
September–October	0.255
November–December	0.267
Average value	0.266

[a]Including fees and taxes for a contract power of 5.5 kW.

Table B.1
Main types of rebound effects.
Source: Own elaboration.

Case	Related s_t^k expression
Expected reduction	$\sum_{\tau^*} p_t^m \lambda \sigma_t^k = 0$
Rebound effect	$s_t^k = \sum_{\tau} p_t^m \sigma_t^k - \lambda \sum_{\tau+\tau^*} p_t^m \sigma_t^k > 0$
Backfire effect	$s_t^k < 0$

where $\tau*$ is the additional use of the new appliance. Table B.1 shows the expressions of rebound effects with increased efficiency.

There is no doubt that these considerations on the behavior of the prosumers can be included in the dynamic model of avoided cost through the relationship between q_0 and the evolution of the level of consumption over time and their comparison with the levels before the installation of the plant. Unfortunately, enough empirical information has not been found.

References

Alanne, K., Saari, A., 2006. Distributed energy generation and sustainable development. Renew. Sustain. Energy Rev. 10 (6), 539–558.

Alrawi, O., et al., 2022. Determining the influencing factors in the residential rooftop solar photovoltaic systems adoption: Evidence from a survey in Qatar. Energy Rep. 8, 257–262.

Argyrou, M., Marouchos, C., Kalogirou, S., Christodoulides, P., 2021. Modeling a residential grid-connected PV system with battery–supercapacitor storage: Control design and stability analysis. Energy Rep. 7, 4988–5002.

Beraldi, P., Violi, A., Carrozzino, G., 2020. The optimal management of the prosumer's resources via stochastic programming. Energy Rep. 6, 274–280.

Bird, J., et al., 2015. Customer-Led Network Revolution. Developing the Smarter Grid: The Role of Domestic and Small and Medium Enterprise Customers. In: Document n. CLNR-L246. Northern Powergrid and Others, Document available at www.networkrevolution.co.uk. (Accessed January 2017).

Brett, D.J.L., Staffell, I., 2015. An introduction to microegeneration. In: Staffell, I., et al. (Eds.), Domestic Microgrid. Renewable and Distributed Energy Technologies, Policies and Economics. Routledge, London, pp. 3–17.

Castillo-Cagigal, M., et al., 2011. PV self-consumption optimization with storage and Active DSM for residential sector. Document available at http://oa.upm.es/13625/2/INVE_MEM_2011_98247.pdf. (Accessed December 2016).

CEER, 2016. CEER Position Paper on Renewable Energy Self-Generation. C16-SDE-55-03. The Council of European Energy Regulators, Document available at www.ceer.eu. (Accessed April 2017).

CSWD, 2015. Best Practices on Renewable Energy Self-Consumption. In: CSWD, 141 final, Commission Staff Working Document, European Commission, Brussels, Document available at http://ec.europe.eu/energy/sites/files/documents. (Accessed June 2016).

Del Río, P., Mir-Artigues, P., 2012. Support for solar PV deployment in Spain: Some policy lessons. Renew. Sustain. Energy Rev. 16, 5557–5566.

Del Río, P., Mir-Artigues, P., 2014. A Cautionary Tale. Spain's Solar PV Investment Bubble. International Institute for Sustainable Developement-GSI, Winnipeg (Ca), Available at http://www.iisd.org/gsi/sites/default/files/rens_ct_spain.pdf.

Ding, Y., et al., 2015. In: Sorensen, B. (Ed.), Solar Electrical Energy Storage. Academic Press, Amsterdam, pp. 7–25.

Dufo-López, R., 2015. Optimisation of size and control of grid-connected storage under real time electricity pricing conditions. Appl. Energy 140, 395–408.

EC, 2017. Study on "Residential Prosumers in the European Energy Union".

EC, 2019. Energy Prices and Costs in Europe. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions, COM(2019)1 final, Available at https://ec.europa.eu/energy/data-analysis/energy-prices-and-costs_en. (Accessed June 2020).

Ellaban, O., Allasi, O., 2019. Integrated economic adoption model for residential grid-connected photovoltaic systems: An Australian case study. Energy Rep. 5, 310–326.
Erdinc, O., et al., 2015. A new perspective for sizing of distributed generation and energy storage for smart households under demand response. Appl. Energy 143, 26–37.
Falabretti, D., et al., 2018. Energy storage coupling in a high efficiency household scenario: A real life experimental application. J. Energy Storage 17, 496–506.
Fitzgerald, G., et al., 2015. The Economics of Battery Energy Storage: How Multi-Use, Customer-Sited Batteries Deliver the Most Services and Value to Customers and the Grid. Rocky Mountain Institute, Document available at www.rmi.org. (Accessed June 2016).
Gährs, S., et al., 2015. Acceptance of ancillary service and willingness to invest in PV-storage-systems. Energy Procedia 73, 29–36.
Gbadega, P., Sun, X., 2021b. Centralized peer-to-peer transactive energy market approach in a prosumer-centric residential smart grid environment. Energy Rep. 8, 105–116.
Gbadega, P., Sun, X., 2022. Primal–dual interior-point algorithm for electricity cost minimization in a prosumer-based smart grid environment: A convex optimization approach. Energy Rep. 8, 681–695.
Goulden, M., et al., 2014. Smart grids, smart users? The role of the user in demand side management. Energy Res. Soc. Sci. 2, 21–29.
Green, M.A., 2019. How did solar cells get so cheap? Joule 3, 631–640.
Green, R., Staffell, I., 2017. Prosumage and the British electricity market. Econ. Energy Environ. Policy 6 (1), 33–49.
Hassan, Q., 2022. Evaluate the adequacy of self-consumption for sizing photovoltaic system. Energy Rep. 8, 239–254.
Hirschman, A.O., 1972. Exit, Voice, and Loyalty. Responses to Decline in Firms, Organizations, and States. Harvard University Press, Cambridge (Mass).
Hoppmann, J., et al., 2014. The economic viability of battery storage for residential solar photovoltaic systems - A review and a simulation model. Renew. Sustain. Energy Rev. 39, 1101–1118.
Hughes, L., 2005. The Economics of Net Metering. In: Halifax, Energy Research Group, University of Dalhousie, Document available at http://www.osti.gov. (Accessed in August 2012).
IEA, 2016. Review and analysis of PV self-consumption policies. Document available at www.iea.org. (Accessed March 2018).
IEA, 2018. Net metering and PV self-consumption in emerging countries. Available at www.iea.org. (Accessed March 2019).
IEA-RETD, 2014. Residential prosumers - drivers and policy options (RE-PROSUMERS). IEA-RETD. Document available at www.iea-retd.org. (Accessed March 2017).
IEA-RETD, 2016. Commercial Prosumers. Development and Policy Options (RE-COM-PROSUMERS). IEA-RETD, Utrecht, Document available at www.iea-retd.org (Accessed March 2017).
Ilham, N., Dahlan, N., Hussin, M., Sintuya, H., Setthapun, W., 2022. An optimal compensation schemes decision framework for solar PV distributed generation trading: Assessing economic and energy used for prosumers in Malaysia. Energy Rep. 8, 536–544.
IRENA, 2016. The Power to Change: Solar and Wind Cost Reduction Potential to 2025. International Renewable Energy Agency, IRENA, Abu Dhabi.
IRENA, 2019. Future of Solar Photovoltaic. Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects. In: A Global Energy Transformation: Paper, International Renewable Energy Agency, Abu Dhabi.
IRENA, 2019a. Net Billing Schemes. Innovation Landscape Brief. International Renewable Energy Agency, Abu Dhabi.
IRENA, 2020. Renewable Power Generation Costs in 2019. International Renewable Energy Agency, Abu Dhabi.
Jager, W., 2006. Stimulating the diffusion of photovoltaic systems: A behavioural perspective. Energy Policy 34, 1935–1943.
Kanakadhurga, D., Prabaharan, N., 2021. Demand response-based peer-to-peer energy trading among the prosumers and consumers. Energy Rep. 7, 7825–7834.
Kazhmiaka, et al., 2017. On the influence of jurisdiction on the profitability of residential photovoltaic-storage systems: A multi-national case study. Energy Policy 109, 428–440.
Kelly, N., et al., 2015a. Integrating microgeneration into smart energy networks. In: Staffell, I., et al. (Eds.), Domestic Microgrid. Renewable and Distributed Energy Technologies, Policies and Economics. Routledge, London, pp. 255–280.
Kelly, N., et al., 2015b. Technical and Economic Modelling of Microgeneration. In: Staffell I, others, (eds) Domestic Microgrid. Renewable and Distributed Energy Technologies, Policies and Economics, Routledge, London, pp. 319–339.
Khalilpour, K.R., Vassallo, A., 2015. Leaving the grid: An ambition or a real choice? Energy Policy 82, 207–221.
Khalilpour, K.R., Vassallo, A., 2016. Community Energy Networks with Storage: Modeling Frameworks for Distributed Generation. Springer, Singapore.
Korcaj, l., et al., 2015. Intentions to adopt photovoltaic systems depend on homeowners' expected personal gains and behavior of peers. Renew. Energy 75, 407–415.
Lara, E., Santos, F., 2021. Review on viability and implementation of residential PV-battery systems: Considering the case of dominican republic. Energy Rep. 7, 8868–8899.
Lauinger, D., et al., 2016. A linear programming approach to the optimization of residential energy systems. J. Energy Storage 7, 24–37.
Li, J., Danzer, M.A., 2014. Optimal charge control strategies for stationary photovoltaic battery systems. J. Power Sources 258, 365–373.
Loewenstein, G., 2009. Anomalies in intertemporal choice: Evidence and an interpretation. In: Lowenstein, G. (Ed.), Exotic Preferences. Behavioral Economics and Human Motivation. Oxford University Press, Oxford, pp. 411–440.
Longe, O.M., et al., 2017. Distributed demand side management with battery storage for smart home energy scheduling. Sustainability 9 (120), 13, www.mdpi.com/journal/sustainability.
Luthander, R., et al., 2015. Photovoltaic self-consumption in buildings: A review. Appl. Energy 142, 80–94.
MacGill, O., Watt, M., 2015. Economics of solar PV systems with storage, in main grid and mini-grid settings. In: Sørensen, B. (Ed.), Solar Energy Storage. Academic Press, Amsterdam, pp. 225–244.
Merei, G., et al., 2016. Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. Appl. Energy 168, 171–178.
Mir-Artigues, P., del Río, P., 2016. The Economics and Policy of Solar Photovoltaic Generation. Springer.
Mohan, V., et al., 2022. Policy assistance for adoption of residential solar PV in India: A stakeholder-centric approach for welfare optimization. Energy Rep. 8, 197–206.
Moshövel, J., et al., 2015. Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption. Appl. Energy 137, 567–575.
Neij, L., et al., 2009. Choice-decision determinants for the (non) adoption of energy efficiency technologies in households. In: ECEEE 2009 Summer Study. Available at http://worksbepress.com/luis_mundaca/13. (Accessed July 2018).
Nemet, G.F., 2019. How Solar Energy Became Cheap. In: A Model for Low-Carbon Innovation, Routledge, London.
Nolan, J.W., et al., 2008. Normative social influence is underdetected. Pers. Soc. Psychol. Bull. 34, 913–923.
Olczak, P., et al., 2021. Analyses of duck curve phenomena potential in polish PV prosumer households' installations. Energy Rep. 7, 4609–4622.
Opiyo, N., 2016. Energy storage systems for PV-based communal grids. J. Energy Storage 7, 1–12.
O'Shaughnessy, E., et al., 2018. Solar plus: Optimization of distributed solar PV through battery storage and dispatchable load in residential buildings. Appl. Energy 213, 11–21.
Poullikkas, A., et al., 2013. A review of net metering mechanisms for electricity renewable energy sources. Int. J. Energy Environ. 4 (6), 975–1002.
Prelec, D., Loewenstein, G, 1997. Beyond time discounting. Mark. Lett. 1 (8), 97–108.
Quoilin, S., et al., 2016. Quantifying self-consumption linked to solar home battery systems: Statistical analysis and economic assessment. Appl. Energy 182, 58–67.
Ramalho, M., et al., 2017. Photovoltaic energy diffusion through net-metering and feedin tariff policies. Learning from Germany, California, Japan and Brazil.
Ratnam, E.L., et al., 2015. An optimization-based approach to scheduling residential battery storage with solar PV: Assessing customer benefit. Renew. Energy 75, 123–134.
Reis, V., Almeida, R., Silva, J., Brito, M., 2019. Demand aggregation for photovoltaic self-consumption. Energy Rep. 5, 54–61.
Seebauer, S., 2018. The psychology of rebound effects: Explaining energy efficiency rebound behaviors with electric vehicles and building insulation in Austria. Energy Res. Soc. Sci. 46, 311–320.
Siemer, L., et al., 2016. Cost-optimal operation of energy storage units: Benefits of a problem-specific approach. J. Energy Storage 6, 11–21.
Skjolsvold, T.M., et al., 2015. A traveler's guide to smart grids and the social sciences. Energy Res. Soc. Sci. 9, 1–8.
Sorrell, S., Dimitropoulos, J., 2007. UKERC Review of Evidence for the Rebound Effect. Technical Report 5: Energy, Productivity and Economic Growth Studies, UK Energy Research Centre, Sussex, Document available at http://www.ukerc.ac.uk. (Accessed May 2010).
Staffell, I., Hamilton, I.G., 2015. Cross-cutting issues for microgeneration. In: Staffell, I., et al. (Eds.), Domestic Microgrid. Renewable and Distributed Energy Technologies, Policies and Economics. Routledge, London, pp. 49–73.
Staffell, I., et al., 2015. The residential energy sector. In: Staffell, I., et al. (Eds.), Domestic Microgrid. Renewable and Distributed Energy Technologies, Policies and Economics. Routledge, London, pp. 18–48.
van der Stelt, S., et al., 2018. Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. Appl. Energy 209, 266–276.
Trotta, G., 2018. Factors affecting energy-saving behaviours and energy efficiency investments in British households. Energy Policy 114, 529–539.

Wittenberg, I., Matthies, E., 2018. How do PV households use their PV system and how is this related to their energy use. Renew. Energy 122, 291–300.
Xiong, X., Qing, G., Li, H., 2022. Blockchain-based P2P power trading mechanism for PV prosumer. Energy Rep. 8, 300–310.
Zipperer, A., et al., 2013. Electric Energy Management in the Smart Home: Perspective on Enabling Technologies and Consumer Behavior. NREL/JA-5500-57586 NREL. www.nrel.gov/publications. (Accessed June 2015).