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Potential of implementation of residential photovoltaics at city level: The case of London

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ABSTRACT

In recent years, reductions in the price of photovoltaic panels and batteries have made them profitable. However, the achievement of grid parity, i.e. whether these systems are cheaper than the national grid for residential users, is still being debated. This paper quantifies the proportion of demand that could be covered assuming that solar-battery adoption is decided based on the maximum profit, the maximum autarky with no extra cost or the maximum autarky with limited extra-cost. A simulation model is developed which performs a half-hourly analysis for one year, considering the solar radiation, the consumption pattern and characteristics of equipment. London is examined using a database gathering consumption from 5567 households. In particular, the techno-economic performance of the systems is studied according to different reward schemes (from a non-subsidized to a high compensation one). Results are discussed according to the optimisation strategy: maximising profit, for users seeking economic performance; and maximum autarky, for users willing independence from the grid. Complementarily, the correlation between characteristics of consumption profiles and autarky is analysed. Results show that installations are profitable for a reward of 0.03 £/kWh, under profit maximisation, and can attain 90% autarky. The injection reward is still essential to make batteries profitable.

1. Introduction

In order to address climate change, countries have historically implemented incentives for the adoption of solar photovoltaic (PV) energy in the residential sector, given the potential of this technology [48]. Within the European Union, self-consumption has been promoted to favour the transition towards more sustainable energy matrices, easing the integration of domestic PV-based facilities [18]. In particular, the solar electricity injected to the grid has been rewarded through favourable feed-in schemes. Under this context, end-users become “prosumers” [20]: producers when they have excess generation, which is fed into the grid, and consumers when their panels do not fully cover the demand. Consequently, residential solar installations become profitable thanks to the feed-in scheme while the national share of renewables increases. Moreover, a battery backup can also be included in order to increase the end-user's flexibility in terms of the buying-selling scheme, making these devices attractive for residential facilities [34].

In recent years, significant reductions in technology prices, particularly solar PV and batteries, together with the increase in renewable generation have led some countries to reduce the incentives [9]. Indeed, discussion about the achievement of grid parity for PV technology has emerged [30]; i.e. whether it has achieved cheaper prices than the utility grid. Some countries report having already reached such a threshold [51]; while some studies still assume non-incentivised or post grid parity contexts [32,39]. Grid parity occurs when an alternative energy source can supply electricity at a levelled cost of electricity (LCOE) lower than the cost of directly purchasing it from the grid. Hence, this concept allows the equalization process of PV-battery systems to be reflected globally, as opposed to the traditional electricity supply technologies. However, the effectivity of grid parity in measuring system performance has been questioned [66], as it does not encompass all the issues involved and the relationship between grid parity and renewable systems' implementation is not clear. Consequently, research is required into the techno-economic performance of PV-battery systems, the injection reward tariff and the achievement of grid parity.

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1.1. Literature review

A key question investigated in the literature of grid parity is under what conditions residential PV-battery systems can become widespread without the need for subsidies or governmental support [16,28,45]. To answer this, the analysis has to take into account the different factors impacting grid parity. Exogenous techno-economic factors such as the development of technology costs, the retail rate of grid power, as well as national policies and feed-in regulations, vary widely by location and drive significant differences in system performance. To address the various factors that lead to the installation of self-consumption systems economic analyses have been proposed at the household level for different solar battery systems [5,14,64], or load management options [33,65]. On the system level, residential PV potentials are estimated and their possible market diffusion paths are assessed [11,37].

For instance [54], analyse different factors influencing PV grid parity at a residential and commercial level in different European markets by means of the net present value of facilities [25]. focus on grid parity of rooftop PV facilities in the United States, concluding that it has not yet been achieved [39]. analyse the attractiveness of rooftop PV facilities in Central-European countries without subsidies and discuss the mechanisms hindering adoption, despite their cost-effectiveness [43]. study how batteries can increase self-consumption of residential PV systems in Sweden [61]. examine the influence of storage on PV facilities in order to reduce grid dependence in Portugal. They conclude that the cost-effectiveness of such facilities will be achieved by 2020 [32]. analyse key European markets, concluding that despite the reduction in technology costs, the decrease of feed-in tariffs has limited investment into domestic PV-based facilities because of the higher risk and exposure of end-users. Finally [30], review the status of PV grid parity in different countries. They find that the solar resources, technology costs, grid prices, environmental issues and grid extension are the main issues influencing grid parity, and depend strongly on time and the characteristics of each market.

The techno-economic performance of PV-battery facilities is closely related to the relationship between the load profile and the production profile, and depends on the regulatory framework and the characteristics of each context [40]. In order to achieve a significant reduction in the utility bill, PV electricity production must occur at peak demand. However, the production profile follows the path of solar radiation, with maximum production in the middle of the day, while at that time demand is usually low for most residential users. In this regard [40], underline the need to work with real generation and consumption data in order to achieve reliable results and avoid overestimating self-consumption [6]. match the real demand-generation data of residential PV-battery users in the United States to study cost-effectiveness for several pricing scenarios [7]. use simulation tools to study the cost-effectiveness of PV-battery residential users in Germany and Ireland, taking into account regulatory and geographical differences. Finally [46], analyse the influence of load control on the cost-effectiveness of PV-battery installations.

Whether grid parity is achieved or not, substantial profits cannot be expected from domestic PV facilities. However, economic profitability is not the only reason for end-users to install PV-battery systems [31]. Studies show that the adoption of PV-battery systems will be driven not only by exogenous factors, like PV and electricity costs, but also endogenous factors like consumer preferences [37]. Indeed, socio-environmental drivers linked to the use of eco-friendly technologies, which in addition reduce dependence on large national energy matrices, are progressively more important to consumers all over the world [17].

In this regard, the idea to be energy self-sufficient and the opportunity to potentially participate in the energy transition triggers a high willingness to pay in household owners [44,55]. These consumers, particularly within European countries, are willing to adopt PV or PV-battery systems even if they lose money by doing so or if the adoption does not represent an additional cost with regard to a full supply through the grid [31]. Under this assumption, the size of the system to be installed becomes particularly relevant and autarky becomes critical for reducing the environmental impact. For instance, the emissions reduction of a system covering 10% of a customer's consumption is not as relevant as a system covering 90% of the demand. The willingness to pay is for these households higher than the achievable savings from the reduced electricity bill. Accordingly, such non-monetary factors should be accounted for in the profitability assessment of domestic renewable facilities in order to align with the current investment motivations [52].

In this context, global measures such as grid parity only partially reflect the potential impact of solar PV in a certain area. The comparison between the cost of obtaining the energy from the grid and from a residential PV facility should be made at facility level, in order to directly contrast the utility price with the load profile. For instance, suppose that grid parity is attained at 150 monetary units and two houses, A and B, have solar installations with a yearly profit of 100 and 200 monetary units, respectively. If the analysis is performed for both houses together, grid parity would be assumed for the whole set, while a more accurate examination would be that only 50% of the households have attained it. In order to better analyse the profitability of residential PV systems technical bottom-up models are most suitable as their high level of detail makes it possible to simulate household's reaction to different factors [27,57].

On the other hand, determining the profitability of PV-battery installations for a certain household is not enough. The implementation of PV panels leads to a partial substitution of power from the grid by self-generated electricity. Hence, the autarky must be determined; i.e. the substitution level reached by the installation. Additionally, maximum profit is not always the criterion used to opt for solar PV adoption. Some users might be interested in maximising the use of panels, although conditioned to no expenditure increase or even a limited loss.

Additionally, as residential demand fluctuates continuously, a high temporal resolution is advisable [53]. As stated by Ref. [40]; the best way to perform the proposed analysis is to work with real load profiles. In this regard, the increasing implementation of smart-meters makes individual load profiles available with a high degree of detail (hourly consumption). To date, significant works in both academic research and industry have been conducted based on smart-meter data [62]. The application areas of smart energy meter data include energy forecasting [56], pricing prediction [2], grid operation [35], customer segmentation [59], energy efficiency [19] and demand response management [1]. However, less attention has been paid to the profitability performance of household PV-battery systems using real load profiles.

The existing techno-economic studies differ in the key variables of interest (for example, optimal configuration of PV power and battery sizes, maximisation of autarky or profitability, etc.), as well as in the input parameters studied and the data used. Table 1 provides an overview of recently published related works and, in the last row this paper, according to the following characteristics, by columns:

- Batteries: indicates whether the use of batteries is considered or not.
- Location: countries analysed.
- No. Load profiles: amount of profiles examined.

Table 1
Overview on recently published PV economic studies.

Study	Batteries	Location	No. Load profiles	Load profile Type	Load profile vs autarky	Reward vs profitability	Reward vs autarky	Optimisation strategy		
								Profitability	Autarky	Autarky with losses
[50]	Yes	Various EU countries	894	S15	No	No	No	Yes	No	No
[24]	No	Sweden	108	R60	No	No	No	Yes	No	No
[7]	Yes	Germany/Ireland	200/200	S30/R30	Yes	Yes	No	Yes	No	No
[43]	Yes	Sweden	2104	R60	No	No	No	No	Yes	No
[67]	Yes	Switzerland	4232	R30	Yes	No	No	Yes	No	No
[47]	Yes	US/Switzerland	305/636	R15	No	No	No	Yes	No	No
[5]	Yes	Germany	960	S15	No	No	No	Yes	No	No
This paper	Yes	UK	5567	R30	Yes	Yes	Yes	Yes	Yes	Yes

- Load profile type: indicates whether the study uses real (R) or synthetic (S) profiles and their temporal resolution. For instance, R30 represents a real profile with a 30-min resolution.
- Load profile vs autarky: specifies whether the article analyses the impact of load profiles on the autarky achieved.
- Reward vs profitability: indicates whether the article analyses the impact of the injection reward on the economic performance of the systems.
- Reward vs autarky: indicates whether the article analyses the impact of the injection reward on the autarky achieved.
- Optimisation strategy: indicates which optimisation strategy is applied (maximisation of the profitability, maximisation of the autarky, or maximisation of the autarky with a percentage of economic losses).

As shown in Table 1, there is a large variety of works in terms of the geographical scope and the load profile data. Most of them solely focus on financial optimisation strategies. Among the studies using real profiles, many do not assess the influence of different injection rewards on the techno-economic performance of the residential PV-battery systems. Yet, while they offer a valuable perspective of residential self-consumption economics, they do not consider autarky (even with economic losses) as an optimisation strategy and do not assess the impact of different reward schemes for the excess solar electricity injected to the grid on the economic performance of the systems.

1.2. Contribution and paper structure

This paper aims to analyse the cost-effectiveness and autarky achieved by residential self-consumption facilities at city level, and estimates the proportion of households for which investment is an attractive option. In contrast to previous studies, which focus on the maximisation of an economic objective, in this work we address three alternative optimisation strategies that take into account monetary and non-monetary decision drivers for household's adoption of PV-battery systems: i) maximum profit, which minimise costs for investors, ii) maximum autarky, according to the concept of grid parity at facility level defined in Section 2.2, and iii) maximum autarky at less than 20% of extra cost.

The UK is progressively reducing the incentives for domestic PV facilities [9]. In this paper, London is used as a case study, taking real consumption profiles from a public database that gathers data from 5567 households [38]. Recent changes in the United Kingdom (UK) regulations make older feed-in tariff schemes no longer viable and question the profitability of residential PV-based systems [26]. Although some studies have already been performed [15,63], further examination of the policy change implications, based on real data, is required. This paper aims to fill this research gap by investigating how different reward schemes for the surplus PV production injected to the grid impact the economics and the degree of autarky of residential PV-battery systems at city level.

In order to carry out the analysis, a simulation model is developed, which considers equipment, solar radiation and consumption data to calculate the techno-economic performance of the systems. Finally, a computation experiment is carried out to determine the techno-economic performance of PV-battery systems in a set of houses of a certain area. A bottom-up approach is proposed, based on calculating the performance of the facilities individually, which considers:

- A set of houses (load profiles).
- Data about the utility grid price, the injection reward, solar radiation and the cost of the equipment used for the PV-battery installation.
- Different optimisation strategies to determine the capacity of the equipment.

Summary figures are then calculated for the whole set of houses. Additionally, the correlation between several characteristics related to the consumption profile (including the households' socioeconomic level, the demand variation, etc.) and the autarky achieved by PV-battery systems are examined.

The remainder of the paper is organised as follows. First, a general description of the methodology used for the analysis provided (Section 2). Then, the databases and other information considered for the case study in London are detailed (Section 3). Next, the results are analysed and discussed, and recommendations for policy-makers are gathered (Section 4). Finally, the conclusions of this work are summarised (Section 5).

2. Methodology

This section describes the simulation model (Section 2.1) and the optimisation strategies (Section 2.2) considered for the analysis of results.

2.1. Simulation model

The studied PV-battery facilities are conceived for households wishing to become as independent from the grid as possible. However, the power contract of grid-connection remains unchanged, since the demand can still be supplied should the PV-battery system not work (because of a failure or the lack of solar radiation for a long period). In addition, the following elements are included: a set of PV panels and a battery bank for electricity storage (whose capacity needs to be optimised according to the consumption of each household) and an inverter and control system to integrate the PV-battery facility with the grid.

In order to design the PV-battery systems and examine the achievement of grid parity at facility level, a simulation model is developed. The model aims to examine the techno-economic performance, carrying out a half-hourly analysis for a year, which allows covering the typical radiation and consumption seasonality. At each period the simulation examines how the demand can be supplied, so that there are no shortages. Logically, electricity from PV panels is prioritised, the excess being stored in the battery bank or, if it reaches full capacity, feeding the grid in exchange for an injection reward. When PV electricity is not enough to cover the demand (for instance, at night hours), the shortfall is supplied either by batteries, if charged enough, or the grid, incurring a grid-tariff cost.

The simulation model takes into account the following input data for studying the techno-economic performance of the PV-battery systems:

- A set of household characteristics, each one with its own consumption profile (consumption level as well as monthly, weekly and daily variability) and Acorn category (representing the socioeconomic level).
- A geographical location of the facilities to be examined, with the corresponding solar radiation profile.
- The techno-economic parameters of the purchase and maintenance of PV panels and batteries, which are assumed to be appropriately installed and managed.
- The internal connexions, inverters and controllers for the correct management of the system, which are assumed to have an average performance.
- The contract with the power utility company, detailing the hired capacity, the cost of power from the grid and the injection reward for PV electricity fed into the grid.

Considering the above information, the simulation model examines the PV panels and battery bank capacity for each studied household (consumption pattern), thereby revealing the individual economic profitability and autarky achieved. In order to be able to globally examine the achievement of grid parity at facility level for the specified geographical location, average values are calculated for the whole set of households studied. In particular, the following results are provided:

- Proportion of viable installations and average profit, as an indicator of the economic performance of the PV-battery systems.
- Average autarky, as an indicator of the technical performance of the PV-battery systems and the independence that can be achieved from the grid.
- Average panel capacity of viable installations, as an indicator of the size of the PV panels.
- Proportion of installations with batteries, as an indicator of the economic performance of such devices, whose profitability is still under discussion.
- Average battery capacity of the installations that include them, as an indicator of the size of the battery bank.
- Average profit as a proportion of consumption cost, taking into account that households with different consumption levels (and consequently different expenses in electricity supply) are compared.

2.2. Optimisation strategies

As explained in the introduction, the decision about the implementation of self-generation PV-battery systems is based on several parameters at a local level, such as the load profile, the grid price, solar radiation, technology costs, etc. Consequently, the achievement of grid parity at a national level is still under discussion [30]. At the facility level, which is the focus of this paper, the concept of grid parity can be understood as follows: a facility has reached grid parity at an X% degree when it is able to cover X% of the demand while remaining cost-neutral.

To illustrate the behaviour at facility level, Fig. 1 represents a typical situation for a household PV system. The horizontal axis refers to the autarky of the system, from a total dependence on the grid (0%) up to full independence (100%). The blue bullets represent the cost of the corresponding electricity supply. A 100 cost is considered as a basis when the demand is fully supplied by the grid. If a small PV system is installed to cover part of the load (10% autarky in the example), the cost increases up to 110 because of the fixed costs of PV panels. From this level, the cost diminishes when increasing the autarky until a minimum value, which in the example is 30% autarky with a cost of 85. This point is commonly sought by most of the reviewed papers in order to minimise the cost for investors. In the example, this situation represents a 15% saving with regard to non-installation of the PV system. From here on, a change of tendency is observed since additional panels cannot be used at full capacity because of the mismatch between generation and consumption, so the PV technology progressively becomes more expensive. Grid parity at the facility level is attained when a maximum autarky is reached at no additional cost; in the example, 60%. This point represents the maximum independence the household can achieve without additional costs regarding the grid supply. Higher autarky levels could be considered, should the household owners be willing to lose money in order to achieve an eco-friendlier system.

Therefore, the simulation model is developed with the aim of considering the following optimisation strategies (i.e. criteria to determine the capacity of the PV panels and the battery bank):

- Maximum profit (MP): the minimum cost PV-battery system is sought for each household studied. This option is for end-users aiming to achieve as much economic performance as possible.
- Maximum autarky without extra cost (MA): the maximum independence from the grid is sought, but without accepting economic losses with regard to the option of not implementing the PV-battery system. This option is for end-users aiming to become as environmentally friendly as possible, at no additional cost.
- Maximum autarky at less than 20% extra cost (MA20): maximum independence from the grid is sought, even if the system is up to 20% more expensive than not implementing the PV-battery system. This option is for end-users willing to pay an additional cost for achieving a more environmentally friendly system.

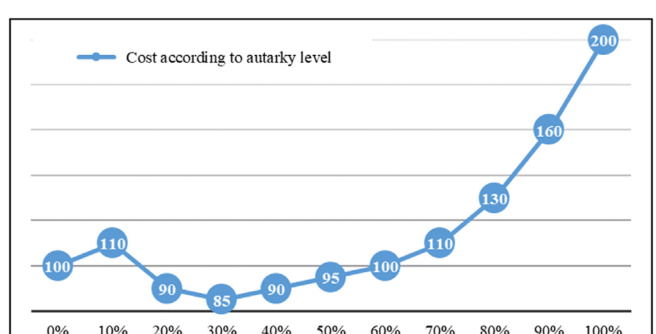

Fig. 1. Level of autarky and total cost of the electricity supply.

3. Methodology and experiment

This section describes the different databases and sources of information taken into account to carry out the analysis of London.

3.1. Load profiles

The performed analysis is based on the publicly available dataset SmartMeter Energy Consumption Data from London, provided by UK Power Networks [38], which has previously been validated and used [12,13]. In particular, the real energy consumption of 5567 households is compiled, organised in half hour slots from November 2011 to February 2014. Moreover, the database includes information about the Acorn segment of each household, which is a classification of residential users taking demographic, social and consumption characteristics in the UK into account [8].

After analysing the dataset in detail, a filtering of information was carried out in order to improve the robustness of the results. First, duplicates were eliminated. Second, as the data for the full period was not available for all the households, only data from the year 2013 was taken into account. This was the year with the highest amount of information and it also comprises a full year-round period, permitting the influence of common seasonal variations on the techno-economic performance of PV-battery facilities to be analysed. Therefore, only households with valid registers for the year 2013 were considered, removing the others and particularly those with a 0 consumption at some periods, which is caused by a technical issue when collecting information. As a result of the filtering, 4677 households were studied.

3.2. Solar radiation

The analysis of the performance of PV-battery systems requires data about the solar radiation at the specific geographical location of the target area examined. This information can be determined from the Centre for Environmental Data Analysis database, which includes hourly solar irradiance information over the UK's territory since 1947 and is regularly updated [10]. Hence, this paper uses data for the calendar year 2013 obtained from the observatory at London Heathrow.

It must be noted that data for the May 10, 2013 was not available, so the hourly radiation was assumed to be proportional to the previous day. Additionally, some adjustments were carried out in order to adjust the data to the half-hour slots from the load profiles. Specifically, half of each hour's solar radiation is assigned to the first half of that hour, while the second half of that hour is estimated through a linear extrapolation taking into account the solar radiation of the following hour. Complementarily, the solar radiation of all the periods is proportionally adjusted according to each day's total radiation.

3.3. Techno-economic parameters

Regarding the solar PV panels, the total output capacity provided by the manufacturer is multiplied by the solar radiation data and the losses throughout the entire PV-battery system, which are estimated at 20%. Concerning the cost of PV panels, even when a specific country is considered, it varies according to the manufacturer, installer, etc. An important issue when selecting the PV panel is the surface occupied. Common modules produce around 180–230 W/m^2 under peak conditions. Panels achieving higher performance are more expensive but are often selected because of space limitations or aesthetic reasons. Indeed, in relatively dense urban areas such as London, they are becoming predominant.

In the literature, indicative prices from commercial websites and catalogues have been commonly used to estimate the cost of solar PV systems [15]. Following this approach, the data provided by one of the most popular commercial websites on solar facilities has been consulted [21]. Price ranges for different installation sizes are shown and, as prices tend to fall over time and London's council is promoting group buying to reduce prices [41], the lowest value of the range has been considered. Hence, a fixed (£2000) and a variable (£1000/kW) cost have been determined, which are consistent with recent works on the UK [15].

Concerning battery storage, limitations according to typical manufacturer indications are established in terms of their operations: a maximum charge speed of 2 h and a maximum discharge speed of 10 h, in order to protect them. Moreover, batteries are considered to be at 0 level at the beginning of the simulation and the charge at the end of the simulation is considered an unused remainder. Most common batteries for solar PV systems are lithium-ion, so these are the devices considered in this paper. Their cost is estimated from a commercial website, which provides a range of values depending on the capacity [22]. Therefore, a fixed (£2400) and a variable (£300/kWh) cost are estimated, which are consistent values with regard to other works on the UK [15]. Note that the variable cost is adjusted taking the useful capacity into account; i.e. considering the maximum depth of discharge of these devices.

Regarding the maintenance cost, an estimated £0.18p/kW of PV capacity is considered, according to the literature [60]. Additionally, when calculating the performance, it must be assumed that the installation cost is amortized over the lifespan of the system. For this purpose, a 20-year linear amortization method is adopted, which is a reasonable and cautious horizon for residential PV-battery systems. Consequently, batteries (lifetime: 7 years) and inverters (lifetime: 10 years) have to be replaced twice and once, respectively, during this time span. In contrast, solar PV panels (lifetime: 25 years) do not need replacement. All the costs (purchase, maintenance and replacement) are proportionally distributed over the 20-year horizon and updated to the current value for the appropriate comparison; the simulation is performed on the basis of a 1-year period.

3.4. Utility grid data

The price of energy from the grid in UK is assumed to be £0.14288/kWh at any moment of the day. Indeed, most of the households included in the dataset described in Section 3.1 had such a standard. On the other hand, the solar power injection reward scheme has recently changed in the UK [58]. Under the current system, this value is freely determined by the utility companies. Based on real tariffs offered by different companies [23], four options for the injection reward (compensation for the PV electricity fed into the grid) are examined: 0.00, 0.01, 0.03 and 0.05 £/kWh. These values range from no return up to a value which is significantly lower than the utility grid prices in most Western European countries.

4. Results

This section examines the results from the computation experiment. First, the results are examined in terms of the performance of PV-battery facilities, identifying the behaviour for different optimisation strategies and injection reward rates (Section 4.1). Then, the influence of different load profile characteristics on the autarky reached by PV-battery facilities is studied (Section 4.2).

4.1. Performance according to the optimisation strategy and injection reward

Table 2 summarises the results obtained for PV-battery systems under the four injection reward scenarios and the three strategies analysed: maximum profit (MP), maximum autarky at no additional cost (MA) and maximum autarky at less than 20% economic loss (MA20). In particular, for each scenario and strategy, the amount of viable installations among the studied instances [%] is shown. Note that viable installations refer to the percentage of households that could adopt a PV-battery facility under the optimisation strategy sought (i.e. economically profitable for MP and MA; and less than 20% of economic losses for MA29). In addition, for the viable installations, the average size of PV panels [kW], the average profit [£/year] and the autarky reached [%] are detailed. The detailed percentage and size of installations using batteries for the obtained results is further analysed in Table 4.

As observed, when the profit is maximised (MP) and assuming the current prices of PV technology with no injection reward, residential facilities are economically profitable for under 30% of London's households. The average size of PV panels is 1.8 kW, the average yearly profit is only £66.0 and the autarky remains at 18.4%. In other words, under these circumstances, PV facilities are not particularly profitable. Meanwhile, if the autarky is maximised (MA), the same percentage of viability is achieved since only the viable installations are considered. However, the size of PV panels almost doubles (3.4 kW) in order to achieve greater independence from the grid (28.8%), although at the expense of reducing the average profit (£22.9).

When maximising the autarky accepting losses (MA20), the viability percentage more than doubles (close to 70%) since households attaining up to a 20% economic loss with regard to never installing PV panels are still considered viable. In this case, the average profit becomes negative (£-95.1), although this is a value that many families might be willing to accept in return for a more environmentally-friendly electricity supply (the autarky more than doubles, to 58.2%). This autarky increase may seem surprising, given that the average size of PV panels remains similar (3.4 vs 3.7 kW), but it is caused by a significantly higher usage of batteries, as detailed later in Table 4.

On the other hand, as could be expected, the viability percentage significantly increases when the injection reward rises; i.e. when the excess PV electricity fed into the grid is paid for. Indeed, from an injection reward of 0.03 £/kWh, which is 21.4% of the grid purchase cost, all the installations become economically profitable and the average size of PV panels increases to the maximum studied value (10 kW). This is caused by the fact that the extra cost for additional PV panels is compensated by the reward for supplying the excess unconsumed electricity to the grid. Autarky levels achieve around 50% for the MP strategy and around 90% for the MA and MA20 strategies. Consequently, subsidized systems enable households to achieve high degrees of independence from the grid, although not a full disconnection.

Table 2
Viability, size, profit and autarky of PV-battery installations.

		Injection reward [£/kWh]			
		0.00	0.01	0.03	0.05
MP	Viable households [%]	29.4	39.1	100.0	100.0
	Average PV size [kW]	1.8	2.4	10.0	10.0
	Average profit [£/year]	66.0	77.2	218.9	718.7
	Average autarky [%]	18.4	25.9	55.5	47.5
MA	Viable households [%]	29.4	39.1	100.0	100.0
	Average PV size [kW]	3.4	4.7	10.0	10.0
	Average profit [£/year]	22.9	31.0	91.8	452.4
	Average autarky [%]	28.5	39.1	89.5	91.2
MA20	Viable households [%]	69.9	77.0	100.0	100.0
	Average PV size [kW]	3.7	5.0	10.0	10.0
	Average profit [£/year]	−95.1	−74.1	57.2	452.1
	Average autarky [%]	58.2	66.8	90.6	91.2

Table 3
Average profit calculated as a proportion of the consumption cost.

	Injection reward [£/kWh]			
	0.00	0.01	0.03	0.05
MP	6.0%	8.1%	39.9%	105.4%
MA	1.8%	2.4%	18.6%	78.4%
MA20	−16.6%	−13.9%	18.5%	78.4%

Additionally, Table 3 summarises the average profit of the households, but making the calculation as a proportion of the consumption cost. This table aims to examine profitability on a relative basis with regard to the usual utility bills prior to installing the PV-battery system. Each value of the table represents the saving (positive values) or extra cost (negative values) generated by the PV-battery system with regard to the situation of fully supplying the demand from the grid. For instance, for the 0.00 £/kWh injection reward and the maximum profit (MP) strategy, an average saving of 6% is achieved. In contrast, when maximising the autarky (MA), the saving decreases and, logically, becomes a loss, if they are accepted (MA20). When the injection reward increases, the PV-battery systems become progressively more profitable, hence achieving higher savings. In the case of 0.05 £/kWh and the MP strategy, an average of 105.4% is achieved, which implies that many users are earning money. If the autarky is maximised, savings of up to 78.4% can be attained.

Regarding energy storage (Table 4), a different trend is observed in each strategy. When the profit is maximised, the number of households using batteries remains low (reaching 13.1% in the peak case) and the average size of batteries is similar (around 10–13 kWh), regardless of the injection reward. Indeed, at current prices these devices are too expensive, so only a few households are willing to install them when the load profile permits taking advantage of storage. In contrast, when the autarky is maximised, the percentage of households using batteries increases, especially when up to a 20% economic loss is allowed. This is because any profit is used to buy additional batteries, in order to increase the independence from the grid and achieve higher autarky levels (see Table 2). This behaviour is emphasized when the injection reward increases, reaching more than 90% usage for 0.03 £/kWh (average size around 15 kWh) and 100% for 0.05 £/kWh (average size 20.0 kWh, which is the maximum capacity studied).

Additionally, the surprising performance of the maximum profit strategy must be highlighted. From 0.00 to 0.03 £/kWh, as expected, the higher the injection reward, the more households use batteries to become more profitable. In contrast, for 0.05 £/kWh the percentage drops, as the reward is high enough to make it more

Table 4
Percentage and size of installations using batteries.

		Injection reward [£/kWh]			
		0.00	0.01	0.03	0.05
MP	Households using batteries [%]	4.0	6.5	13.1	1.8
	Average battery size [kWh]	11.4	11.0	10.3	13.2
MA	Households using batteries [%]	14.7	21.0	90.4	100.0
	Average battery size [kWh]	12.0	12.3	14.4	20.0
MA20	Households using batteries [%]	43.7	50.0	95.8	100.0
	Average battery size [kWh]	11.1	11.7	15.9	20.0

profitable for most households to sell the excess electricity to the grid rather than buy storage capacity. In order to better explain this behaviour, consider the instance MAC000003, with an annual consumption of 7010.2 kWh. The cost of such consumption fed directly from the grid (without any panel) at the purchase cost of 0.14288 £/kWh is £997.4. The system has a PV capacity of 10 kW, which generates 26,872.4 kWh/year and costs 780.0 £/year.

Table 5 summarises the results for the studied instance when increasing the battery capacity from 0 to 20 kWh, the studied values. The size of batteries (Battery), the amount of PV electricity injected to the grid (Injection), the electricity consumed from the grid (Grid) are shown in the first group of columns. In addition, the fourth column (Remain) takes into account small deviations caused by the installation of batteries. In the following groups of columns, the corresponding values in economic terms are detailed. In particular, the second group of columns shows the cost of batteries (Battery), the electricity consumed from the grid (Grid) and the remaining electricity (Remain).

Concerning the injection, the results are differentiated depending on whether the injection reward is 0.03 or 0.05 £/kWh. In this way, an economic balance is calculated for each battery size (Profit). This balance represents the saving made by using a PV-battery system instead of directly consuming all the electricity from the grid (which, as mentioned before, has a cost of £997.4). For instance, if a 2.5 kWh battery capacity is considered, the cost of the 10 kW PV panels is £780, the batteries £157.5, the electricity consumed from the grid £638.3 and the income from the electricity injected to the grid is £730.5 for the 0.03 £/kWh injection reward. Therefore, considering the remain column deviation, the global cost for this option is £845.1, which represents a saving of £152.3 with regard to fully supplying the demand through the grid (£997.4).

As observed in Table 5, when the injection reward is 0.03 £/kWh the maximum profit is achieved for a battery size of 12.5 kWh, obtaining a profit of £219.0. In contrast, the maximum profit for 0.05 £/kWh is £713.8 when no batteries are installed. In other words, even though an increase in the injection reward should presumably increase the size of the batteries (as happens from 0.00 to 0.03 £/kWh, see Table 4), in the event of the reward reaching a certain limit value (0.05 £/kWh) the opposite effect is observed. In this case, it is better to feed any excess electricity from the PV panels into the grid, rather than buy storage devices. Logically this behaviour goes against autarky, so a decrease in autarky is observed in Table 2, from 55.5 to 47.5% when moving from 0.03 to 0.05 £/kWh.

4.2. Analysis of the influence of load profile characteristics on autarky

In order to complement the above analysis, the correlation between different characteristics of the load profile and the autarky reached by the PV-battery systems is examined (Table 6). In particular, the following aspects are studied: the Acorn aggregated level, as a measure of the household wealth (ACORN); the household's total annual electricity consumption (CONS); the monthly (MONTH) and weekly (WEEK) variability, to identify whether the consumption is uniform and the daytime consumption (DAY). All of these factors are expected to have some relationship with the autarky level attained. Table 6 shows the correlation for each factor, according to the three optimisation strategies (MP, MA and MA20) and the four injection reward scenarios (0.00, 0.01, 0.03 and 0.05 £/kWh). Note that the correlation ranges from −1, for an inverse behaviour of each factor with regard to the autarky, to 1 for a proportional behaviour, moving through 0 which would be an independent relationship.

Table 6
Correlation between different load profile characteristics and the autarky.

ACORN	CONS	MONTH	WEEK	DAY
0.007	**0.200**	−0.091	−0.045	0.085

As observed, the highest correlation value is attained for the consumption factor: the higher the household's consumption, the higher the autarky reached. This happens because high electricity consumption enables taking more advantage of PV panels and hence reduces dependence on the grid. Of equal importance, the higher the daytime consumption, the higher the autarky. Indeed, when most consumption is concentrated in daylight hours, it allows more advantage to be taken of PV panels, so the independence from the grid increases. Meanwhile, the higher the monthly and weekly variability, the lower the autarky. Variability in consumption is detrimental for autarky as PV generation remains similar for successive months or weeks. Finally, the Acorn level does not seem to be significantly correlated with the autarky; which is an interesting conclusion from the social perspective in order to further spread the use of such PV-battery systems among the population.

5. Conclusion and policy implications

The achievement of residential grid parity is a matter of discussion and calculations based on global values are not representative of the performance in each household. This paper examines residential users individually and quantifies those having reached grid parity and to what degree. For this purpose, a simulation model is developed to analyse 5567 real load profiles in London, available thanks to the increasing implementation of smart-meters. The model includes data about the load profile of each household, the utility grid price, the injection reward, solar radiation and the cost of the equipment used for the PV-battery installation. In addition, different optimisation strategies are considered for

Table 5
Detailed results for the instance MAC000003.

Amount [kWh]				Value [£]			Value [£] Inj. Reward 0.03		Value [£] Inj. Reward 0.05	
Battery	Injection	Grid	Remain	Battery	Grid	Remain	Injection	Profit	Injection	Profit
0.0	25,244.5	5382.3	0.0	0.0	765.8	0.0	757.3	209.0	1262.2	713.8
2.5	24,348.6	4486.5	1.2	157.5	638.3	0.2	730.5	152.3	1217.4	639.2
5.0	23,629.5	3767.4	3.4	195.0	536.0	0.5	708.9	195.8	1181.5	668.3
7.5	23,135.7	3273.5	3.4	232.5	465.8	0.5	694.1	213.7	1156.8	676.4
10.0	22,762.0	2899.9	4.9	270.0	412.6	0.7	682.9	218.4	1138.1	673.6
12.5	22,425.3	2563.1	6.9	307.5	364.7	1.0	672.8	219.0	1121.3	667.5
15.0	22,153.9	2291.8	9.1	345.0	326.1	1.3	664.6	212.3	1107.7	655.3
17.5	21,981.6	2119.5	11.6	382.5	301.6	1.7	659.4	194.5	1099.1	634.1
20.0	21,834.3	1972.1	14.1	420.0	280.6	2.0	655.0	173.9	1091.7	610.5

optimising the size of PV panels and batteries, depending on whether they favour the maximum profit, the maximum autarky or the maximum autarky accepting a small economic loss.

Results show that when maximising profit, and considering no injection reward, PV facilities are not particularly profitable. If the maximum autarky is sought, the size of PV panels increases in order to increase the autarky level by around 10%; while if economic losses up to 20% are accepted, an additional 20% autarky is gained. When the injection reward increases, logically, PV systems progressively become more profitable. For a compensation rate of 0.03 £/kWh (21.4% of the utility grid price), all the installations achieve profitability, as the cost of PV panels is compensated by the income obtained from the electricity injected to the grid. Under these conditions, 90% autarky can be attained for the maximum autarky strategy, although full disconnection is not achieved. Regarding batteries, these devices are still very expensive, but their usage can be spread thanks to the injection reward, especially if the maximum autarky is sought. In that case, any income from the electricity injected to the grid is used to purchase additional batteries that increase independence from the grid. Moreover, when the profit is maximised, increasing the injection reward above a certain threshold (0.03 £/kWh) makes it preferable to feed electricity into the grid rather than buy storage devices. Additionally, the correlation between different consumption profile characteristics and the levels of autarky achieved are examined. The results show the highest influence on autarky is caused by consumption levels, as higher demand enables taking more advantage of PV panels.

This paper can be useful for administrators, as it enables quantifying the performance of PV-battery facilities under different optimisation strategies and injection rewards, in order to aid in defining policies oriented towards the energy matrix transition to accomplish the United Nations 2030 sustainability objectives. As future research, additional case studies must be examined, and particularly without limiting the analysis to residential users, but including commercial or industrial facilities.

CRediT authorship contribution statement

J. Olivella: Conceptualization, Methodology, Software, Writing – original draft. **B. Domenech:** Term, Conceptualization, Methodology, Validation, Writing – original draft. **G. Calleja:** Term, Conceptualization, Validation, Writing – review & editing, Formal analysis.

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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