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ORIGINAL ARTICLE

Household energy consumption and the financial feasibility of self-consumption through photovoltaic panels in Spain

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Abstract Energy consumption is one of the main costs faced by households, both financially and environmentally. This article analyses the energy consumption of Spanish households and the cost of installing solar panels in order to determine the potential of this form of energy production on a household level. The results show that households with a larger number of members have a higher total consumption but a lower consumption per person. The composition of the household is therefore a key determinant of the potential savings from solar panels. This alternative is financially viable, as the unit price paid for energy in these households is between €0.28 and €0.29 per kilowatt-hour (kWh), while the average cost per kWh obtained from the panels is between €0.15 and €0.21. However, the current public subsidies for the installation of solar panels in Spain are inaccessible to 68% of the country's households, and there are difficulties in the distribution of energy in neighbouring communities. In other words, although in financial terms home PV self-consumption is a financially viable option, the inability to obtaining subsidies makes the initial investment a major barrier for many households.

Keywords Energy policy · Energy prices · Energy self-consumption · Household characteristics · Photovoltaic energy

Introduction

Energy is one of the fundamental elements of human activity, with consumption increasing as a country or region develops (Zhang et al, 2021). Today, many activities cannot be carried out without an adequate supply of energy, which justifies Sustainable Development Goal 7 (ensure access to affordable, reliable, sustainable and modern energy for all). Households use energy for cooking, washing clothes, lighting and other activities, so an adequate source of energy is essential. This aspect is of great importance, as such a supply represents a significant financial cost to them, as well as an environmental cost due to the use of non-renewable energy sources and the associated pollution. Of course, households are not the only energy consumers to take into account, as others, such as water services, are also large consumers, which is why their energy supply has been analysed and efforts have been made to reduce their consumption (Langarita et al, 2016; Melgarejo & Montano, 2011; Yusta Loyo, 2016). As with water services, reducing household energy costs would lead to financial and environmental savings, either through the application of energy efficiency measures or via the use of alternative energy sources (Pardo et al., 2020).

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In this sense, the generation of energy through photovoltaic solar panels is one of the main alternatives due to its constant technological improvement, which has enjoyed cost reductions and production increases (UNEF, 2020c), and its flexibility (Simões et al, 2022). In addition, investments in self-consumption of energy through solar panels are usually eligible for public sector subsidies.

The photovoltaic sector has developed intensively in recent years and the average cost of this energy source has decreased significantly (IRENA, 2019; Jäger-Waldau, 2019; UNEF, 2020c). This is of great importance for the financial viability of photovoltaic projects, as the cost of energy supply can be one of the most important costs (Yusta Loyo, 2016; Zarzo & Prats, 2018). This is initially the case, but in the long term there are economic and environmental benefits that provide a return on investment (Arazola-Martínez, 2019). In Spain, electricity generation using these panels has grown in recent years and generation capacity is expected to continue to increase (IRENA, 2019; UNEF, 2020c). Spain is also one of the countries in Europe with the most hours of sunshine (Prieto, 2017), so the potential for solar energy is very high. However, there are many aspects that affect the energy production of solar panels and therefore their average cost (Deb & Brahmbhatt, 2018). Therefore, proper project design and maintenance are essential factors that promote the generation and consumption of this type of energy (Hanes, Gopalakrishnan & Bakshi, 2018; Tovar Ospino, 2010).

The potential financial and environmental benefits of self-consumption with photovoltaic solar panels are not sector specific. As discussed above, water utilities are often considering the incorporation of photovoltaic panels with the aim of reducing their environmental impact and operating costs (JCU, 2020; Setiawan et al, 2014). Increased business competitiveness can also be achieved by reducing the financial costs of energy supply (González & Alonso, 2021; Moreno et al, 2014) and households could also enjoy savings on their electricity bills and other savings from public subsidies. Furthermore, the development of the sector would be associated with an increase in economic activity and employment, which is very useful in a situation such as that caused by the COVID-19 crisis (UNEF, 2020b). Despite the positive effects, there are some negative aspects that hinder the development of solar panels as an energy alternative. The most important are the high initial financial costs (Urmee et al, 2018) and the lack of support from the public sector, which manifests itself in a lack of financial support and excessive bureaucratic requirements (Solarplaza, 2020; SolarPower, 2020). In response to these problems, subsidies to cover part of the financial costs have been recently published in Spain (Ministry for Ecological Transition and the Demographic Challenge, 2021), and the Valencia Region has reduced the necessary formalities to encourage this type of project (Generalitat Valenciana, 2020). Finally, since solar panels have a lifespan of 25–30 years (Malandrino et al, 2017; Xu et al, 2018), the design of photovoltaic panels should include this issue and facilitate future recycling and reuse of panel materials (UNEF, 2020a, 2020d).

However, the presence of negative aspects limits the development of solar electricity generation through solar panels. High initial financial costs and a lack of public sector support reduce the number of projects of this type, despite the benefits they bring in the long term. Household self-consumption of energy through solar panels is one of the main strategies to reduce their electricity bills and greenhouse gas emissions (Hesselink & Chappin, 2019; Zhang et al, 2017). Moreover, solar panels are not necessarily a standalone alternative, but can be part of a suite of energy-saving measures based on smart homes (Ghazvini et al, 2017). However, households are often unable to afford the investment required to install panels, nor are they able to calculate the long-term benefits as energy prices change over time (Damette et al., 2018). In any case, family income and energy prices are key considerations for all households when considering the installation of solar panels, so that financial support from the public sector could be useful. Such support would also help to reduce income inequalities, as it is more important for low-income households than for high-income households (Schleich, 2019). In summary, existing barriers to PV self-consumption have limited its growth, so that its potential has not been realised and there is significant room for improvement (Rosenow et al, 2018). Therefore, information campaigns on the benefits of solar panels, reduction of bureaucratic processes and capital support may be helpful (Hesselink & Chappin, 2019). Reducing the uncertainty of solar panel projects by using power generation and cost simulation software to estimate panel performance before the installation is also valuable (Kassem et al., 2019).

For this reason, a number of economic instruments have been put in place to provide incentives for photovoltaic self-consumption. For large-scale production, the main incentives are: (1) feed-in tariffs (FIT), (2) green certificates with a quota system, (3) fiscal and investment incentives, and (4) tenders for the quota system (Sarasa-Maestro et al., 2013). However, many of the incentives cannot be applied at the household level, where the main instruments are financial support, tax rebates and the establishment of compensation for unused electricity fed into the grid (Luthander et al, 2015). Among these incentives, subsidies that cover part of the investment to be made at the time of installation are the most effective (Dusonchet & Telaretti, 2010). The design of any policy must be precise, as the same incentive can lead to different results in different countries or household types (Bertsch et al., 2017; Dusonchet & Telaretti, 2010). Given the potential benefits of PV self-consumption, economic incentives have become increasingly common in different countries (Luthander et al, 2015), as they not only contribute to energy substitution, but incentives can also guide PV installations to the optimal size (Mateo et al, 2018) and promote the use of batteries, thus making self-consumption more reliable (Zakeri et al, 2021).

Focusing on the Spanish incentives, the Spanish government has recently published subsidies for the installation of solar panels with an initial budget of 660 million euros, which could rise to 1.32 billion euros when the above is completed (Ministry for Ecological Transition and the Demographic Challenge, 2021). These subsidies are available to companies, public institutions and individuals, although households without a single-family home are excluded. For the latter, the government expects 40,000 households to benefit, with the aim of installing solar panels and reducing their consumption of energy from the grid (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021). In the Valencia Region, for example, aware of the bureaucratic barrier, the necessary procedures for the installation of solar panels have been simplified in 2020 (Generalitat Valenciana, 2020). These policies are added to the already existing subsidies with the aim of developing a form of energy production that has so much potential in the Mediterranean area and in Spain in particular (Prieto, 2017). Since this paper the focuses on Spanish households due to the available data, it is worth commenting on the other types of subsidies that exist in Spain. These subsidies consist of deductions in different taxes, such as the personal income tax (IRPF by its Spanish acronym), the property tax (IBI by its Spanish acronym) and the tax on construction, installations and works (ICIO by its Spanish acronym) (Otovo, 2020). There is also a subsidy that covers part of the investment cost, but this subsidy is not available to households that are part of a community of neighbours. In other words, whether it is a national or regional subsidy, households that do not own a single-family house do not have access to financial support for self-consumption through solar panels. Despite these subsidies, the bureaucracy involved in installing solar panels is costly in terms of time and money and limits the development of solar panels even when the subsidies are available. These procedures are divided into the permits required for the installation of solar panels (five procedures) and the procedures required after installation (eight procedures) (Hilcu, 2021). In total, there are 13 steps to be taken, which explains why the Valencian government is trying to reduce this bureaucracy.

The recent evolution of the price of electricity represents a significant increase in the cost of living, as it is not only one of the main household expenses, but also a key determinant of the price of the rest of the products consumed. Therefore, given the benefits of self-consumption of solar energy and the available subsidies, it is interesting to analyse the current financial viability of installing solar panels in households. With this aim, the current situation regarding household energy consumption and the financial results derived from the self-consumption of energy through solar panels are analysed. In this way, this work defines the financial situation regarding energy the self-consumption of energy through solar panels in households. This is very useful for the implementation of information campaigns aimed at communicating to citizens the financial benefits they can obtain from self-consuming energy, which would contribute to the reduction of greenhouse gas emissions. It is also very useful information for the design of new subsidies to stimulate the development of photovoltaic panels. This article presents, for the Spanish case, a broad picture of the situation of household energy consumption, of the possibility for households to proceed with self-consumption and of the current design of public subsidies for the installation of photovoltaic panels. This analysis, in a country with a high electricity price and many hours of sunshine, such as Spain, is an interesting case study, as a greater effort in the development of photovoltaic self-consumption would be expected. In order to achieve the proposed objective, after this introduction, the first step is to explain the data used and the methodology applied are explained. Then, the energy consumption of Spanish households is analysed. This is followed by the cost of installing solar panels in homes and the financial viability of these projects, which will be developed in the discussion and conclusions sections.

Data and methodology

Data

The data used to meet the proposed objective come from two different sources. First, the data on household energy consumption come from the Household Budget Survey of the Spanish National Statistics Institute (INE). Specifically, the latest available edition is used, which is published in 2021 and contains data for 2020. This survey covers all household expenditure, so it is not an energy-focused database. However, as energy is a household expenditure, these data allow us to assess aspects such as energy consumption, the price paid for it and other aspects of households such as their income, composition or the proportion of their budget devoted to their energy bill. These types of variables, which have been shown to be significant in other cases (Damette et al., 2018; Schleich, 2019), will be the focus of the analysis at the household level. In addition, other variables such as population density, municipality size and region of residence will be included in the analysis. Consumption variables are expressed in kilowatt-hour (kWh), price variables in euros (€), income in thousands of euros and the weight of the bill on the income is in percent. The remaining variables are categorical. The variables on household composition refer to the category of single adult household.s The population density, which can be low, medium or high, the category "low" is excluded. The size of the municipality is divided into several categories: 1) less than 10,000 inhabitants; 2) between 10,000 and 20,000 inhabitants; 3) between 20,000 and 50,000 inhabitants; 4) between 50,000 and 100,000 inhabitants; and 5) more than 100,000 inhabitants. In this case, the variables refer to the smallest municipality size, i.e. 10,000 inhabitants or less. Finally, the region variables refer to the region with the lowest energy consumption per household, which is Castilla y León. It is worth noting that some observations have been eliminated because they were very far away from most of the households. In particular, observations with a price per kWh higher than €2, a total bill higher than €7,000, a bill per person higher than €3,500, a logarithm of the total bill lower than 2 or an income higher than €200,000 have been removed. These criteria have eliminated very specific households, as only 13 observations out of a total of 18,142 were eliminated, leaving a final sample of 18,129 observations. In addition, each of these observations has an associated sample weight, which indicates how many households it represents. On the other hand, the Continuous Household Survey have been used to identify how much households are eligible for public subsidies, which allows, for the purposes of this article, to know how many households are of each type.

On the other hand, in order to calculate the financial aspect of energy self-consumption, the data provided by the company Enerficaz make it possible to analyse the financial situation of Spanish households with regard to energy self-consumption of energy through solar panels. This part of the analysis is based on households in the Region of Valencia, since this is the area for which information on the installation of panels is available.

Methodology

The data used are processed in two main ways. Firstly, the econometric technique of Ordinary Least Squares (OLS) with robust errors is used with the aim of providing information on the payment situation of households for energy supply. In estimates that seek to explain energy consumption or price, these variables are included on a logarithmic scale, so that the coefficients can be interpreted as elasticities. On the basis of the available information, four estimates are made depending on whether the household energy consumption, the consumption per person, the unit price or the weight of the bill on the income is being analysed, using the following equation:

$$X_h = Y_h\beta + \varepsilon_h \quad (1)$$

where X represents the variable to explain; Y is a vector of individual explanatory variables and a constant term; β is a vector of parameters and ε is a random error term. The subindex h refers to the unit of analysis used, households.

On the other hand, the financial situation of energy self-consumption with solar photovoltaic panels is analysed through the payments made by the households and the budgets obtained for the installation of the panels. In this way, the cost of traditional supply and the cost of supply with solar panels are available, so that comparisons can be made between the two alternatives. Due to the characteristics of solar energy production, it is not intended to completely replace the traditional energy supply. In addition, Enerficaz states that selling excess energy or installing batteries to store it are not viable alternatives for households, as unused electricity is sold to the grid at a price far below the cost of generation and the price of batteries is currently very high. It is therefore assumed that all the energy produced will be used immediately, which is why the aim is to satisfy only 60% of the household's electricity consumption. This part of the analysis focuses on the total investment, the annual savings obtained from the solar panels, the point at which the solar panels become profitable and the total financial benefits obtained at the end of their life. Based on the project data provided by Enerficaz, the annual savings are calculated as the market price of the energy produced (energy generated multiplied by the unit price of traditional supply). The cost of self-consumption derived from the information provided by Enerficaz already includes all costs that may arise during the lifetime of the PV panels, including both the replacement of the inverters and the cost of operation and maintenance, which is calculated as 1% of the initial investment. By dividing the total investment to be made by the annual savings, it is possible to determine the year after installation in which the investment will be amortised. It is important to note that the energy generated by the solar panels is maintained for the first 5 years, after which it is reduced by 5% each year due to panel degradation caused by factors such as panel quality, installation and maintenance and climatic and environmental conditions.. This rate is higher than those obtained in the technical analyses, which include a degradation of between 0.56% and 0.8% per year (Youssef et al, 2018; Gonzalo, Marugán & Márquez, 2020), but it is the figure provided by the company. Therefore, in the calculations made, the energy generated is maintained for 5 years, and then reduced to 5% per year.

Results

Household energy consumption

The first results, shown in Table 1, are the mean and standard deviation of the main variables of interest. It can be seen that, except for the unit price, the differences between household types are quite large. In other words, the payments made for something as basic as electricity supply depend on factors that are independent of income or household structure. The growth in consumption as the household size increases is therefore valuable information. However, while total consumption increases, consumption per person decreases, income increases and the weight of the bill on household income decreases. In brackets, Table 1 shows the standard deviation, which shows that these differences are not only between groups, but that there are also large different within the same groups, i.e. households of the same structure. Therefore, given the large differences between and within groups, it is to be expected that the econometric estimates will show large differences.

After the descriptive information in Tables 1 and 2 shows the results of the econometric estimation concerning the situation of households with respect to their electricity bills and their energy consumption. With regard to energy consumption, there are two estimates, depending on whether consumption per household or per person is analysed. At the household level, the variables of municipality size and population density do not show a clear pattern, although they show higher energy consumption in larger cities. Households show an elasticity of -1.047, indicating a strong response to changes in energy price.

Table 1 Mean and standard deviation (in parentheses) of the main variables of interest for the types of households studied

Household type	Energy consumption per household (kWh/year)	Energy consumption per household per person (kWh/year)	Household members	Unit price (€/kWh)	Monthly income (€)	Ratio of electricity bill to income (%)[1]
One adult without children	2,126.02 (1351.91)	2,126.02 (1351.91)	1 (0.00)	0.29 (0.09)	1,416.27 (828.10)	4.34 (3.52)
Two adults without children	2,755.94 (1795.21)	1,377.97 (897.60)	2 (0.00)	0.29 (0.08)	2,221.31 (1171.41)	3.52 (2.75)
Other households without children	2,530.72 (1473.55)	1,078.44 (677.09)	2.46 (0.64)	0.29 (0.08)	1,491.28 (809.84)	5.01 (4.30)
One adult with at least one child	3,259.59 (2115.06)	996.56 (635.43)	3.33 (0.61)	0.28 (0.09)	2,834.91 (1523. 02)	3.27 (2.59)
Two adults with one child	3,042.71 (1819.72)	1,014.24 (606.57)	3 (0.00)	0.29 (0.09)	2,540.72 (1334. 98)	3.46 (2.84)
Two adults with two children	3,285.19 (2030.94)	821.30 (507.73)	4 (0.00)	0.29 (0.09)	2,778.37 (1478.01)	3.44 (3.02)
Two adults with three or more children	3,315.18 (2225.72)	628.59 (412.48)	5.28 (0.55)	0.28 (0.07)	2,899.70 (2028.31)	3.66 (3.73)
Other households with children	3,589.94 (2193.86)	759.46 (462.15)	4.84 (1.15)	0.29 (0.10)	2,931.40 (1634. 12)	3.57 (2.80)

[1]The ratio of electricity bill to income is not exactly the same as the ratio of electricity expenditure to annual income because of the weighting factor associated with each observation. This factor implies that each observation represents a different number of households. The higher the weighting factor, the more households the observation represents and the greater its importance in the calculations. This means that each value in the table has been calculated taking into account this variable and what is shown are weighted averages. The weight on the bill calculated here is also a weighted average of the weights of different observations representing different numbers of households. If, instead of calculating the weighted average of the ratio of electricity bill to income, the data in this table were used to calculate the direct value, the result would be different due to the lack of weighting

Income is also significant, which is very important, because in the same way that it conditions consumption, it affects the household's capacity to install solar panels. In this case, higher income is associated with higher consumption. However, the interaction of rent with price is not significant, which means that income and price are important individually, but not together. On the other hand, the household type variables show that consumption is higher as the number of household members increases with the exception of households with 2 adults and 3 or more children, which is quite reasonable and it is a result that has already been obtained before (Debs & Metzinger, 2022). Finally, the regional variables show large differences in consumption according to place of residence. It should be remembered that these variables refer to the region with the lowest consumption per household. However, no specific pattern is found either, as there are no common factors such as location or climate to explain the differences in consumption between regions.

If consumption per person is analysed instead of consumption per household, the results are very similar, with the exception of the variables by household type. This aspect, together with others such as household consumption, disposable income and the unit price they pay, is very important in determining the ability of households to engage in energy self-consumption. Therefore, the next variable to be analysed is the unit price.

Again, municipality size and population density do not show a clear pattern in relation to unit price. As household consumption increases, the unit price decreases due to the presence of a fixed component that is divided into more and more consumption. In terms of household type, as with consumption, the unit price increases with the number of household members. Assuming that consumption grows according to the size of the household, these last results seem to contradict each other. However, the two effects are independent and, since there is an

Table 2 Estimates of Eq. 1 explaining the consumption per household and per person, the unit price and the weight of the electricity bill on the household's net income

	Energy Consumption per household	Energy Consumption per person	Unit Price	Weight of the invoice
Town of between 10,000 and 20,000 Inhabitants	0.075	0.073	0.071	0.102
	(0.018)***	(0.018)***	(0.008)***	(0.066)
Town of between 20,000 and 50,000 Inhabitants	0.077	0.080	0.003	0.298
	(0.025)***	(0.025)***	(0.010)	(0.113)***
Town of between 50,000 and 100,000 Inhabitants	0.106	0.106	0.058	0.300
	(0.027)***	(0.028)***	(0.012)***	(0.134)**
Town of more than 100,000	0.096	0.097	0.012	0.158
	(0.028)***	(0.028)***	(0.012)	(0.123)
Average Population Density	-0.025	-0.021	-0.025	-0.215
	(0.016)	(0.016)	(0.007)***	(0.093)**
High Population Density	-0.057	-0.054	-0.016	-0.043
	(0.026)**	(0.026)**	(0.011)	(0.122)
Income of the Household (Thousand €/year)	0.006	0.010	0.001	-0.109
	(0.001)***	(0.002)***	(0.000)***	(0.003)***
Energy Consumption (kWh)	-	-	-0.203	0.001
	-	-	(0.005)***	(0.000)***
Unit Price (€)	-1.047	-1.074	-	6.095
	(0.039)***	(0.035)***	-	(0.318)***
Unit price*Income	-0.002	0.002	-	-
	(0.004)	(0.008)	-	-
Two adults without children	0.215	-0.391	0.043	-0.404
	(0.014)***	(0.014)***	(0.006)***	(0.065)***
Other households without children	0.321	-0.710	0.054	-0.331
	(0.018)***	(0.018)***	(0.007)***	(0.085)***
One adult with at least one child	0.188	-0.580	0.034	0.366
	(0.025)***	(0.028)***	(0.010)***	(0.159)**
Two adults with one child	0.311	-0.648	0.069	-0.359
	(0.018)***	(0.018)***	(0.007)***	(0.081)***
Two adults with two children	0.355	-0.858	0.071	-0.313
	(0.018)***	(0.018)***	(0.007)***	(0.102)***
Two adults with three or more children	0.283	-1.178	0.036	0.105
	(0.038)***	(0.038)***	(0.014)***	(0.174)
Other households with children	0.415	-0.947	0.091	-0.272
	(0.025)***	(0.024)***	(0.010)***	(0.109)**
Andalusia	-0.188	-0.185	0.101	0.710
	(0.030)***	(0.030)***	(0.008)***	(0.151)***
Asturias	-0.250	-0.243	0.177	0.080
	(0.034)***	(0.034)***	(0.012)***	(0.142)
Balearic Islands	-0.381	-0.360	0.130	0.151
	(0.033)***	(0.033)***	(0.011)***	(0.147)
Canary Islands	-0.382	-0.393	0.059	0.000
	(0.033)***	(0.033)***	(0.013)***	(0.156)
Cantabria	-0.321	-0.310	0.171	0.279
	(0.032)***	(0.032)***	(0.009)***	(0.155)*

Table 2 (continued)

	Energy Consumption per household	Energy Consumption per person	Unit Price	Weight of the invoice
Castilla and León	-0.319	-0.307	0.297	0.205
	(0.034)***	(0.034)***	(0.014)***	(0.166)
Castilla-La Mancha	-0.154	-0.148	0.271	0.456
	(0.034)***	(0.034)***	(0.013)***	(0.166)***
Catalonia	-0.226	-0.216	0.094	0.184
	(0.030)***	(0.030)***	(0.008)***	(0.135)
Valencia	-0.207	-0.198	0.057	0.366
	(0.031)***	(0.031)***	(0.009)***	(0.146)**
Extremadura	-0.278	-0.265	0.152	0.418
	(0.037)***	(0.037)***	(0.012)***	(0.159)***
Galicia	-0.297	-0.290	0.112	0.077
	(0.031)***	(0.031)***	(0.010)***	(0.138)
Madrid	-0.236	-0.233	0.079	0.306
	(0.031)***	(0.031)***	(0.009)***	(0.137)**
Murcia	-0.081	-0.081	0.166	0.511
	(0.033)**	(0.034)**	(0.010)***	(0.156)***
Navarra	-0.302	-0.289	0.130	0.511
	(0.038)***	(0.037)***	(0.011)***	(0.176)***
Basque Country	-0.376	-0.361	0.117	0.278
	(0.030)***	(0.030)***	(0.008)***	(0.138)**
La Rioja	-0.329	-0.312	0.176	0.213
	(0.035)***	(0.035)***	(0.013)***	(0.148)
Ceuta	-0.449	-0.491	-0.078	1.456
	(0.086)***	(0.089)***	(0.065)	(0.428)***
Melilla	-0.334	-0.346	-0.087	0.842
	(0.061)***	(0.062)***	(0.026)***	(0.299)***
Constant	6.299	6.158	0.116	1.948
	(0.063)***	(0.062)***	(0.040)***	(0.205)***
R^2	0.35	0.48	0.31	0.54
N	18,129	18,129	18,129	18,129

*$p < 0.1$; **$p < 0.05$; *** $p < 0.01$

explanation for the decrease in the average price as a function of consumption, it would be useful to pay more attention to the characteristics of the households, which is not possible with the data used in this article. Although this aspect does not affect the pricing, as this is done privately by the supplier, it is of great relevance for the installation of solar panels. For example, a household with fewer members pays a lower unit price and is likely to have a lower income, making it more difficult for these households to opt for self-consumption of energy. On the other hand, households with more members, paying a higher unit price and having a higher total consumption and income, would be more likely to use solar panels for self-consumption. Finally, the regional variables show large price differences depending on the place of residence. Again, however, there is no clear pattern that allows us to identify regional characteristics that determine the price.

The last of these estimates makes it possible to analyse the weight of the electricity bill on household income. The size of the municipality and population density do not show a clear pattern, although they are significant. Of course, in this case, income has a negative effect on the weight and price has a strong positive effect. The most important part of this estimation is to analyse the differences in the importance of the bill for different household types and regions. In terms of household type, the high weight of the electricity bill as a proportion of income for households with one adult and one or more children stands out. This makes sense, as these households have only the income of the adult, but several people consuming energy. Single person households and households with two adults and three or more children have a significantly lower weight than the previous household type, but a higher weight than the rest of the households included in the analysis. Therefore, this estimate indicates that households consisting of one adult, one adult with children or two adults and three or more children have the highest potential for energy savings relative to the weight of their electricity bill. However, two of these three household types have only one adult, so they may find difficult to make the necessary investment to proceed with energy self-consumption. On the other hand, households with two adults and three or more children have a higher income and significant savings potential, so they would be the type of households that could most easily make the investment in solar panels. Finally, most of the regional variables are not significant, so there is no evidence of important regional differences in this respect. Some regions show a significant positive coefficient, indicating that people in these places is paying a higher proportion of their income on household bills. It should be remembered that there was no clear regional pattern in terms of price and consumption, so it is difficult to justify this situation. Consumption, price and income are the main aspects explaining the weight, but even when they are included in the calculations there are differences without a clear pattern. This may affect the distribution of national subsidies, as they are set in a common way for all regions and could be unevenly distributed.

In summary, the results obtained are in line with the existing literature and point to price, income and household structure as the key variables for analysing households energy bills and their capacity to engage in self-consumption through solar photovoltaic panels (Damette et al., 2018; Debs & Metzinger, 2022; Schleich, 2019). Income and price are key determinants of energy consumption (Damette et al., 2018) and determine the investment capacity of households (Schleich, 2019) and the value of the energy produced by solar panels. To this must be added the importance of household structure, which affects the consumption, income and other household expenditures (Debs & Metzinger, 2022).

Cost and financial viability of self-consumption of energy using solar panels

The company Enerficaz provided data on the financial costs of installing solar panels in single-family homes, highlighting some details. Firstly, there are currently no plans to develop self-consumption projects that produces more energy than is consumed, as the economic return that households receive for the surplus that is fed into the grid does not compensate for the costs involved. Secondly, the installation of batteries to store energy that is not consumed is not considered either, as their cost is very high. However, these costs are expected to fall in the coming years. Thirdly, because of the previous two points, the installation is always considered to produce around 60% of the household's energy consumption in the first few years.

Table 3 shows, among other things, the energy consumption of each type of household and the consumption that should be covered by solar panels. Obviously, the more people there are in the household, the higher the consumption, although the consumption per person is actually lower. Enerficaz states that a 1.6kWp system is capable of generating between 1,500kWh and 1,600kWh per year. In this analysis the lowest value is used, as not all households are well oriented. This is the average amount of energy that the panels will produce during the first five years of operation. From this point onwards, the energy generation is reduced by 5% each year, as specified in the methodology. As this is the minimum amount of energy that a panel can produce in this region, there are no households in a worse situation than the one presented, but there are others whose energy generation would be higher. For this analysis, the lifetime of the solar panel is assumed to be 25 years (Malandrino et al, 2017; Xu et al, 2018). Finally, the financial cost of these installations is 1,600 euros per kWp, in addition to the 21% Value Added Tax (VAT), which can be reduced to 10% in certain situations. To this must be added the cost of the formalities to be carried out and the maintenance of the panels throughout their

Table 3 Key elements about the financial situation of the installation of solar panels

Household type	Energy consumption (kWh/year)	Energy to be produced initially (kWh/year)	Power term (kWp)	Installation cost plus maintenance cost (€)	Household income (€/month)	Total energy produced (kWh)	Unit price traditional supply (€/kWh)	Cost of traditional 25-year energy supply of the energy produced (euros)	Households as a percentage of total (%)
One adult without children	2,126.016	1,275.61	0.85	4,646.39	1,416.27	21,926.16	0.29	6,358.587	19.60
Two adults without children	2,755.939	1,653.56	1.10	5,134.19	2,221.31	28,422.66	0.29	8,242.571	30.74
Other households without children	2,530.716	1,518.43	1.01	4,959.79	1,491.28	26,099.94	0.29	7,568.983	3.85
One adult with at least one child	3,259.594	1,955.76	1.30	5,524.23	2,834.91	33,617.1	0.28	9,412.789	12.71
Two adults with one child	3,042.705	1,825.62	1.22	5,356.27	2,540.72	31,380.16	0.29	9,100.246	11.67
Two adults with two children	3,285.185	1,971.11	1.31	5,544.05	2,778.37	33,880.95	0.29	9,825.476	13.73
Two adults with three or more children	3,315.179	1,989.11	1.33	5,567.28	2,899.70	34,190.35	0.28	9,573.298	2.39
Other households with children	3,589.939	2,153.96	1.44	5,780.04	2,931.40	37,023.92	0.29	10,736.94	5.3

lifetime, especially as not all the components of the installation have a lifetime of 25 years.

Table 3 shows the calculations made to analyse the capacity and potential savings for households to proceed with self-consumption. The costs shown for the installation of solar panels include the cost of installation, the cost of the necessary paperwork, taxes and the costs incurred over the lifetime of the solar panels, including the replacement of the inverters. However, bureaucratic costs can vary from region to region, so it is important to bear this in mind when trying to extrapolate the analysis. The results in Table 3 are quite clear, so they will be discussed briefly. Of course, more populated households have a higher consumption and therefore require more energy production. Consequently, the potential savings for these households are higher. As the energy demand increases, so does the power term and the financial cost. In other words, all aspects are related to the size of the household, as both income and energy consumption are higher in larger households. It should be noted that the unit price paid by households is similar regardless of their type. For this reason, high-consumption households have the greatest savings potential, as they consume more for a similar price. Significant savings can be achieved by households of all types by using solar panels for self-consumption. Even a single-person household can make financial savings of around €1,712.20 over the lifetime of the solar panels. The potential savings increase with the number of household members, reaching a maximum benefit of almost €5,000 in the last household typology. These are 25-year results, i.e. the annual benefit is not particularly high, but it is a benefit that can be very important for households with tight budgets, in addition to the environmental benefit to society. These data imply that for a single-person household, the solar panels will reach profitability in the 15th year after installation, while in the latter type of household this would be reached in the 10th year. These results do not take into account any public support or the fact that there is a fixed element in the electricity bill, so the actual savings could differ from those found in this research. However, as will be shown in the following section, it is absolutely essential to analyse the situation of households and who can actually proceed to self-consumption through solar panels and benefit from public subsidies. Otherwise, public policies aimed at stimulating the development of solar photovoltaic solar panels will not be effective.

Discussion

The data on household energy consumption and on the financial costs of installing solar panels in homes have provided valuable information on the development of self-consumption through solar panels. On the whole, solar panels are clearly profitable, as they produce energy at a lower cost than the price paid for traditional supply. This is a situation that has already been observed in other countries, such as Germany (Fett et al, 2019), the United Kingdom (Dong et al, 2020), Ireland (Bertsch et al., 2017) and Sweden (Nyholm et al, 2016), where there are fewer hours of sunshine than in Spain. However, a complete replacement of energy consumption is more difficult to achieve due to the high cost of batteries and the environmental impact they have at the end of their useful life (Johann & Madlener, 2014; Vieira et al., 2017). In any case, the potential savings are high and self-consumption with solar panels is justified.

However, there are two key aspects to consider when determining which households are potential solar panels purchasers. In this regard, it is necessary to distinguish between the characteristics of the dwelling and the financial situation of the household (Roth et al, 2020). In Spain, most households live in dwellings that are part of a community of neighbours, which severely limits their ability to use solar panels for their own consumption. This is because the panels would be connected for the whole community of neighbours, so that an individual would never make the investment to only get a small part of the savings. Recently, the possibility of solving this problem through technological changes, such as the use of energy storage sharing on a neighbourhood community scale has been considered (Roberts et al., 2019). D'Agostino et al. (2022) showed the potential in terms of self-consumption in a neighbourhood community, which is a clear indication of the importance of paying attention to this type of consumer. However, the distribution of the energy produced is still a major barrier to self-consumption in the communities of neighbours. In the hypothetical case that one of these communities would agree to install solar panels and they could share the electricity through technical changes, they do not form a valid legal entity to apply for aid for the installation of solar panels. Therefore, the type of dwelling in which one lives is a direct determinant of self-consumption through solar panels, since being part of a community of neighbours requires the agreement of the different neighbours and financial aid cannot be applied for. According to data from the Spanish National Statistics Institute's Continuous Household Survey (ECH for its Spanish acronym), there are approximately 18.75 million households in Spain, of which only around 5.95 million are single-family households, i.e. slightly less than 32% of Spanish households are single-family households. Clearly, this is a significant number and the potential savings are high, but the subsidies are currently exclude 68% of the country's households. Furthermore, the government estimates that only 40,000 single-family homes will benefit from the newly announced subsidies, which is a small fraction of the approximately 5.95 million existing single-family homes. This case is a good example of the importance of the design of public incentives for self-consumption. Each case must be carefully analysed, as the economic performance of the panels is not the same in all countries and households and incentives must be adapted, as the case of France shows (Roth et al, 2020). For example, the use of an electric car is associated with higher electricity consumption. In a country with a higher use of these vehicles, higher household consumption would be expected, so that a factor independent of self-consumption would be relevant in its development and would affect the effectiveness of incentives for the installation of solar panels. Without a complete analysis of potential users, the current Spanish case, which has been in place since 2019 when bureaucracy was reduced and self-consumption incentives were introduced (Prol & Steininger, 2020), could occur, where technical difficulties and the lack of incentives beyond tax incentives for neighbourhood communities mean that support for self-consumption in households is concentrated on relatively high incomes.

From a financial point of view, self-consumption by means of photovoltaic solar panels has proved to be feasible, as it is able to reduce the unit cost of energy consumed by households from the 0.28–0.29€/kWh of traditional supply to the 0.15–0.21€/kWh of self-consumption. The data from this study have also showed large differences in income between the different types of households. The electricity bill of Spanish households represents between 3.27% and 5.01% of household income, which indicates a certain capacity for savings. This issue has a direct impact on the capacity of households to make the necessary investments for installation and the bureaucracy involved in self-consumption. The question is which households will need financial support from public authorities to cover the high initial investment. Low-income households are less likely to own a single-family house than high-income households, preventing the installation of solar panels. For households that do not own their own home, it would not make sense to call for subsidies, as they would not be effective, but in any case the current subsidies exclude a very large number of households. These subsidies are available for single-family homes, which are likely to have a higher average income than homes that are part of a community of neighbours. Therefore, while current subsidies can help pollution from energy production, they are targeted at a segment of households that are likely to have the means to use solar panels on their own and are leaving other households out. In a community of neighbours, the energy may be relatively easy to use due to the presence of several consumers, although this would need to be checked on a case-by-case basis, as users may not be at home, e.g. going to work, to consume the electricity produced during sunny hours. In other words, all of the energy produced could be used, but no support would be available.

The final major determinant of photovoltaic self-consumption is the price of electricity on the grid. In recent years, the price of electricity has fluctuated, making it difficult to calculate the savings on the bill resulting from self-consumption. A large development of this type of project would change the energy mix, with a corresponding effect on the average cost and price of electricity, thus affecting savings. In other words, both public incentives and the decision to invest in self-consumption must take into account that savings are variable and that the performance of the panels will be affected if the use of electricity sources varies. The constant search for new, reliable, cheap and clean sources of energy may lead to major changes in the future that will affect projects implemented nowadays.

In summary, the characteristics of the dwelling, the household and the price are the factors that influence the likelihood that consumers will decide to install solar panels. Current subsidies aim to encourage households to install solar panels, although direct subsidies currently only benefit a very specific segment. It has already been proved that technical solutions and self-consumption potential exist in neighbourhood communities, but the current design of incentives in Spain prevents their exploitation (D'Agostino et al, 2022; Roberts et al., 2019). Therefore, although subsidies can be useful to stimulate the development of solar panels in this segment, the rest of Spanish households need a different type of stimulus to proceed with self-consumption. The main problem lies in the large number of non-single-family households in Spain, where self-consumption cannot be subsidised because they are part of a community of neighbours, not to mention households that do not own their own house. Some newly constructed residential buildings have solar panels built into the roof during construction. Installing solar panels on new buildings, especially on the roof to save space and to reduce land costs and visual impact (Al-Quraan et al, 2022; Hołuj et al, 2021), is useful but leaves out all existing structures. In short, there are solutions for single-family homes and new buildings, but there are currently no incentives to encourage the rest of the families, which make up the majority of Spanish households and have a lower average income, to move towards self-consumption through solar panels, despite the high cost of traditional energy supply. As has been shown in previous cases in different countries, incentives are not equally effective depending on the characteristics of the country and the household (Bertsch et al., 2017; Roth et al, 2020). In this sense, and considering the number of low-income households, it is worth mentioning that reducing energy consumption is another great alternative, but it shows other conditioning factors such as building, region, house, housing equipment, season and climate characteristics (Oota et al., 2021). Finally, it should be noted that, although this analysis is focused on Spain, specifically its regulations, sunshine hours and household characteristics, the methodology and logic behind the results can be extrapolated to other countries with the only particularity being the adaptation of these specific issues. Some of the references cited such as Damette et al. (2018), Schleich (2019) and Debs and Metzinger (2022) show a similar logic, so this article joins an international literature that provides a better understanding of the energy situation of households, what are the main problems are and what solutions are available.

Conclusions

This work has provided useful information for analysing the energy supply situation of Spanish households. The energy consumption of these households and the possibility of self-consumption through solar panels have been analysed. This was possible thanks to data from the Spanish National Statistics Institute and information provided by the company Enerficaz.

In terms of household energy consumption, the price naturally provides an incentive to save. Households with fewer members have lower total energy consumption, but consumption per person decreases as household size increases. The consumption of single-person households amounts to 2126.02kWh, which is the lowest consumption per household but the highest per person, in contrast with households with two adults and 3 or more children, whose total consumption is 3315.18kWh but whose consumption per person drops to 628.59kWh. This is a good example of the importance of the household structure in analysing not only the energy consumption of Spanish households, but also the potential of self-consumption through solar panels. Variables related to the size of the municipality, population density and region of residence do not show a clear pattern, although they have been shown to be relevant.

The second part of the analysis focuses on the current situation regarding the capacity of households to engage in self-consumption through solar panels. This has proven to be financially viable, as the unit cost of energy produced by solar panels is €0.15–0.21/kWh, which is lower than the cost of traditional supply, which is €0.28–0.29kWh. However, the current public subsidies in Spain, which are designed to encourage self-consumption, exclude the 68% of households in the country that do not own a single-family house. Households with a single-family home are also likely to have a higher income, so the households left out of the subsidy are likely to be the ones that need the most help, but they are part of a community of neighbours, which greatly limits the possibility of installing solar panels. This is without taking into account how many households live in rented accommodation. The analysis has therefore shown that the current subsidies, while having a positive effect, are insufficient and do not address the whole problem. New buildings and single-family homes can benefit from self-consumption through solar panels, but the rest of the houses, which are a large part of them, are completely left out of the picture. It is importance for the Spanish public sector to take a broader view of the development of solar panels in order to minimise pollution from energy generation. This information from the Spanish case can also be very useful for other countries seeking to develop solar energy generation by their households, as they will be able to see what aspects they need to take into account when designing the procedures and public subsidies linked to the installation of solar panels. The analysis has shown the enormous importance of the appropriate design of public subsidies, in which the characteristics of the households and the dwellings in which they reside play an essential role. In conclusion, this analysis has shown the crucial importance of offering new alternatives to families who do not own a single-family home, and how subsidies designed to promote self-consumption must include the characteristics of the households and their dwellings.

An accessible, reliable, sustainable and modern energy supply is part of the Sustainable Development Goals. However, not only is the current supply unsustainable, but Spanish subsidies also have an inequality component. Only single-family households, i.e. those with the highest incomes, can apply for subsidies for photovoltaic self-consumption. The high incomes are receiving subsidies while the low incomes cannot even consider the possibility of self-consumption. With current electricity prices, much more attention should be paid to the supply of low-income households, as their electricity bill represents a higher proportion of the total household budget and they have fewer alternatives.

Finally, it should be noted that this work has some limitations. Firstly, it is not possible to analyse the evolution during the year or during the day of energy consumption, nor the production of solar panels during the year, since the data are annual. Secondly, differentiate between households according to the type of dwelling and to look more closely at the issue of single-family dwellings and neighbourhood communities is also impossible. This lack of household-specific information makes it difficult to calculate exactly how much energy would be generated by the panels. The analysis has shown how the public sector needs to think about new solutions for users who are not eligible for public subsidies. This question contributes to a very interesting line of research, as developing new solutions for all households that are excluded from public subsidies and from the benefits of solar panels could be of great benefit to these households.

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Declarations

Conflict of interests The authors declare that they have no conflict ofinterests.

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