Journal of Infrastructure, Policy and Development 2024, 8(6), 5205.
https://doi.org/10.24294/jipd.v8i6.5205

Article

Evaluation of proposals from key suppliers of small-scale photovoltaic installations for single-family homes considering current regulations and environmental and economic criteria—A case study in Malaga, Spain

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CITATION

de Gálvez EN, Cantal LRP, Zamora FJO, et al. (2024). Evaluation of proposals from key suppliers of small-scale photovoltaic installations for single-family homes considering current regulations and environmental and economic criteria—A case study in Malaga, Spain. Journal of Infrastructure, Policy and Development. 8(6): 5205. https://doi.org/10.24294/jipd.v8i6.5205

ARTICLE INFO

Received: 13 March 2024
Accepted: 22 April 2024
Available online: 10 July 2024

Abstract: The economic viability of a photovoltaic (PV) installation depends on regulations regarding administrative, technical and economic conditions associated with self-consumption and the sale of surplus production. Royal Decree (RD) 244/2019 is the Spanish legislation of reference for this case study, in which we analyse and compare PV installation offers by key suppliers. The proposals are not optimal in RD 244/2019 terms and appear not to fully contemplate power generation losses and seem to shift a representative percentage of consumption to the production period. In our case study of a residential dwelling, the best option corresponds to a 5 kWp installation with surplus sale to the market, with a payback period of 18 years and CO_2 emission reductions of 1026 kg/year. Demand-side management offers a potential improvement of 6%–21.8%. Based on the increase in electricity prices since 2020, the best option offers savings of up to €1507.74 and amortization in 4.24 years. Considering costs and savings, sale to the market could be considered as the only feasible regulatory mechanism for managing surpluses, accompanied by measures to facilitate administrative procedures and guarantees for end users.

Keywords: photovoltaic; self-consumption; CO_2 emission reduction; electricity cost savings; Royal Decree 244/2019

1. Introduction

A major problem today is climate change, largely resulting from contemporary lifestyles of advanced societies requiring vast amounts of energy and natural resources. The result is an increase in CO_2 emissions into the earth's atmosphere, which have gone from 280 ppmv in the pre-industrial period (Garduño, 2004) to 418 ppmv (NASA, 2022a). This increase has been accompanied by an increase in the average temperature of the earth's surface of 1.01 °C between 1880 and 2021 (NASA, 2022b). Climate change is partially responsible for biodiversity loss (Cavicchioli et al., 2019) and for environmental disasters such as heatwaves, droughts, etc. (Xu et al., 2018). To prevent serious environmental risk, the Intergovernmental Panel on Climate Change (IPCC) has proposed limiting warming to no more than 1.5 °C of the pre-industrial level, and warning that, if this level is exceeded, drastic steps will need to be taken in regard to energy transition, urban planning, infrastructure development, etc. (IPCC, 2018).

One action being implemented by different governments is to promote use of photovoltaic (PV) installations (solar panels). In mainland Spain, as shown in **Figure**

1, installed PV power has increased from 1 MW in 1994 to 14,593 MW in 2021 (REE, 2022).

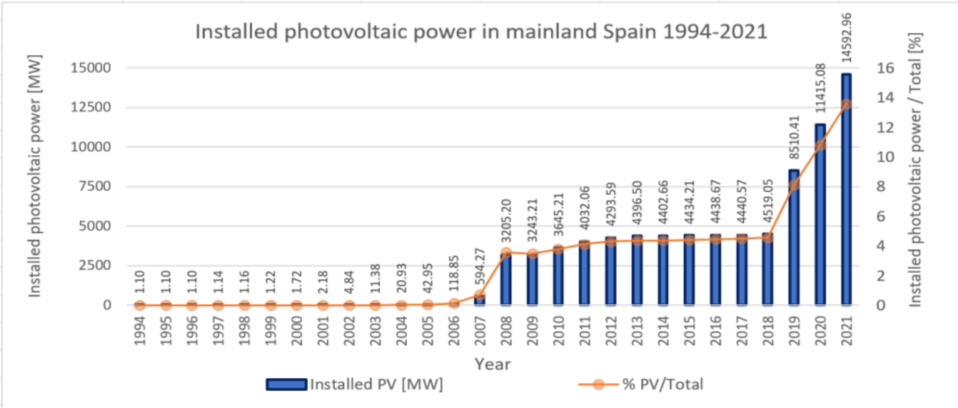

Figure 1. Photovoltaic power (PV) installed in mainland Spain 1994–2021 (Source: Red Eléctrica de España).

This evolution in installed PV power in Spain has reflected a gradual adaptation to the regulatory framework. Representing as it did under 1% of total installed power until 2007, the use of this technology for power generation was anecdotal until Royal Decree (RD) 661/2007 gave an important boost to investment in PV technology, which, as a share of total installed power, increased from 0.71% in 2007 to 3.58% in 2008. There then followed a period of stagnation until 2019, due to regulatory changes that, rather than encourage, discouraged PV power generation; one such regulation was RD 900/2015, widely referred to as the “sunlight tax". Growth recovered in 2019 as a result of technological advances, decreased production costs and grid parity with commercial electricity (IEA, 2015; UNEF, 2013; EPIA, 2011). Growth was further boosted by the new European Directive on Renewable Energies for self-generation and self-consumption, transposed in Spain as RD 244/2019, and also by the grants that were offered for this type of installation (UNEF, 2018).

This new scenario is completed by the optimization studies that have been carried out for this type of small power installations in the residential sector. Studies in reference to the use of active demand-side management (ADSM) in homes located in Spain, presenting possible improvements in photovoltaic use of up to 26% (Castillo-Cagigal et al., 2011). whereas a study of 200 single-family homes in Sweden reported only a limited impact (Widén, 2014). Other proposals for the residential case and with current regulations RD 900/2015 offer negative internal rate of return values of −1.51% in the best scenario (Prol and Steininger, 2017). Studies that limit the increase in self-consumption between 2%–15% due to demand-side management (DSM) (Luthander et al., 2015). On the other hand, there are also studies that emphasize the strong impact that self-consumption policies have on the sizing of photovoltaic installations and the effect that these can have on the electrical network in the form of thermal increases and voltage (Mateo et al., 2018), although other authors claim that self-consumption contributes to the stabilization of the network (Thebault and Gaillard, 2021).

From the above, the concern, need and possible effects of changing the electric energy generation model from fossil fuels to other sustainable alternatives, such as photovoltaic production, can be extracted. Photovoltaics in Spain have received a significant regulatory boost since 2019. This situation has been perceived by leading distributors as an important market niche. To monetize this circumstance to the maximum, these distributors, based on their own or associated installers, began a program of actions and proposals to potential producers of photovoltaic electricity (neighboring communities, owners of detached homes...), supported by a reduction of the electricity bill and CO_2 emissions. These proposals were specified in offers that included photovoltaic installation and subsequent purchase/sale regime for electrical energy.

Our main objective will be to answer the question: are the proposals of these installers the best from an environmental and economic point of view?

Analyzing the proposals of different companies for a case study, compared to the proposal of our work team, which contemplated market costs of the facilities, energy, losses due to orientation, inclination, cell temperature, shadows, mismatch, dust, dirt, wiring, module/inverter quality, demand-side management, and foreseeable evolution of electricity consumption, we will see that the proposals of the different companies did not offer the best fit to the client's needs, but were generic solutions with a series of implicit considerations that could not be appropriate for the client, and consequently may not be suitable for them, it is always recommended to complement the proposals of these installers, with detailed studies adjusted to each case.

2. Materials and methods

Selected for our case study was a single-family semi-detached house located at C/Rio Grande 30, Las Lagunas de Mijas, in Malaga (postcode 29651), 36°32′26″ N–4°38′33″ W, north hemisphere, with contracted power of 5750 W. The two-story house with a total built area of 135 m^2 (see **Figure 2**) has a gabled roof of a total surface area of 68.44 m^2, inclined 10° with respect to the horizontal and longitudinally oriented 40° west with respect to the south.

Figure 2. Floor plan and view of the dwelling in Malaga. Ten solar panels (the maximum possible number) occupy 70% of the surface area (34.22 m^2) of the southwest-facing roof slope, while the remaining 30% is reserved for maintenance purposes (Source (images): Google Earth).

Quotations were requested from established installation companies to fit PV panels on the roof.

Household electricity consumption for 2020 was broken down by time bands and organized by months so as to determine a typical day per month and time band, i.e., the consumption of each time band of a typical day was taken as the average consumption for that time band for each day of the month.

Data on solar radiation and temperature profile downloaded from the PVGIS website (PVGIS, 2022) to the PVGIS-SARAH solar radiation database reflected a typical day each month (local time), the location of the studied dwelling, 10º inclination and 40° azimuth (with respect to the south).

The roof installation was modelled for a PV solar module of 2.41 m^2, 500 W peak, power-temperature coefficient −0.34%/℃ and nominal operating cell temperature (NOCT) 43°.

The power generated at the point of maximum power was calculated using Equations (1) and (2) as follows:

$$P_{mpp} = P_{mpp\ STC}\left[1 + \frac{\gamma\%/_{\circ C}}{100}(T_c - 25)\right]\frac{G}{G_{STC}} \tag{1}$$

$$T_c = T_a + G\,\frac{NOCT - 20}{800\,W/_{m^2}} \tag{2}$$

where:

P_{mpp} is the power in W at the point of maximum power in the studied conditions, P_{mpp} *STC* is the power in W at the point of maximum power in standard conditions (irradiance 1000 W/m², spectrum AM 1.5 and T_a (ambient temperature) 25 ℃), %/℃ is the power-temperature coefficient, T_c is the cell operating temperature in ℃, G is irradiance in W/m^2 in the studied conditions and time band, G_{STC} is irradiance in standard conditions of 1000 W/m^2, T_a is ambient temperature in °C, and *NOCT* is the nominal operating cell temperature in conditions of 800 W/m^2, T_a 20 ℃ and wind speed 1.5 m/s.

The calculated power was corrected by applying a coefficient of 0.9 to account for losses due to mismatch, dust and dirt, wiring and converter and module quality (Osorio and Montero, 2016). Losses due to generator shading by adjoining buildings were analysed using a graph of sun trajectory, distance and relative height difference between the generating field and the shadowing obstacle. Production was aborted whenever the generator was shaded.

Electricity cost was determined for each month based on installed peak PV power for both the simplified compensation and surplus sale to the market systems, as defined in RD 244/2019 (IDAE, 2020). Obtained by time bands from the information system (REE, 2022) of the Spanish electricity network operator (Red Eléctrica de España; REE) were the following: active energy billing components for the Voluntary Small-scale Consumer Price (PVPC) discriminated in two-time bands (DHA 2.0); prices for surplus self-consumption energy for the simplified compensation mechanism (PVPC) for the regulated market, and market daily spot prices for Spain. As with consumption, a typical day was determined by time bands per concept and month, taking the average values for all the days of the month for each time band. Regarding the free market, costs were applied as specified by the supplier.

Used as a reference to calculate savings was billing corresponding to PVPC DHA 2.0 without a PV installation.

To calculate PV installation costs, material component costs based on data published online by commercial companies were compared and further completed with labour and equipment costs as provided by installation companies with a market in the sector during 2020 of 100 kilowatt peak (kWp) installed. From the costs of materials, labour and equipment, a linear function with a fixed term and a variable term based on the installed peak power was used to calculate the final installation cost.

As efficiency criteria, the ratio between the final installation cost and annual cost savings was taken as the economic criterion, while the reduction in CO_2 emissions (calculated from tCO_2equivalent/MWh; (REE, 2022)) was taken as the environmental criterion. Economic and environmental efficiency parameters were calculated for the different offers and the annual savings and amortization periods as indicated in each offer were analysed. The calculations were based on installations of 1 kWp to 5 kWp, for the regulated market with simplified compensation and with surplus sale to the market. To determine the most efficient PV installation according to our efficiency criteria, free-market offers were compared, regulated market offers were compared, and these in turn were compared with each other. Taken as the maximum power that could be injected into the grid was 50% of the contracted power.

Potential cost savings were analysed by transferring the same percentage of hourly demand between 19:00 h and 24:00 h to the solar production period between 11:00 h and 15:00 h, with 20% of the total transferred demand added at each hour. Five demand management alternatives were evaluated: 10%, 20%, 30%, 40% and 50%.

Finally evaluated was the impact of increased electricity costs since the beginning of the study until 2022.

A main limitation of the above-described method is that it is based on a single typical day per month, with the values of each typical day broken down by hours. Another limitation, aimed at reducing the impact that the installation may have on the grid (Mateo et al., 2018), is the imposition of a grid injection limit of 50% of contracted power as a qualitative criterion. And finally, the study is developed on a generic home, common in the housing stock present in the town and province, which is characterized by coexisting with buildings, or elements of greater height that are likely to produce shadows, by presenting oriented and inclined roofs according to building needs associated with the plot…

3. Results and discussion

3.1. Data

The most relevant data for an economic and environmental study of a small-scale PV installation in Spain are the regulations in force, irradiance and temperature, the end user's consumption profile, the energy purchase and sale prices and the costs of installation. Below we review the data used and their sources.

3.1.1. Regulatory environment

The critical issue in determining the economic viability of a PV installation is the regulatory environment governing the administrative, technical and economic conditions associated with self-consumption and the sale of surplus production, as have been established in Spain by RD 244/2019.

Obtained as follows were low-voltage supply costs: power standing charge and active energy tariffs of €38.043426/kW·year for power, and €0.062012/kW·h and €0.002215/kW·h for DHA 2.0 period 1 and period 2 energy, respectively (Order IET/107/2014); supply costs of €3113/kW·year (Order ETU/1948/2016); tax on the value of electricity production (IVEE) of 7% (Law 15/2012); electricity tax of 5.11269632% (Law 38/1992), meter rental cost of €0.81/month (Order IET/1491/2013); and representation costs of €5/MW·h (RD 413/2014) . As determined by RD 1167/2001, period 1 was 11:00–21:00 h in winter and 12:00–22:00 h in summer, with period 2 reflecting the remaining hours.

3.1.2. Irradiance and temperature

PVGIS (2022) is freeware developed by the European Union that provides, as well as an hourly temperature profile values (shown in **Table 1)**, hourly irradiance values (shown in **Table 2)** for a typical day of each month in local time, based on location, inclination and azimuth.

Table 1. Average daily temperature per month and typical day, in local time (Source: PVGIS).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Local time	**Average daily temperature (°C)**											
0:00	13.05	13.22	14.2	15.51	17.9	20.62	23.3	23.9	22.1	19.35	15.89	14.19
1:00	12.88	12.93	13.83	15.16	17.45	20.1	22.75	23.59	21.89	19.22	15.81	14.03
2:00	12.66	12.66	13.57	14.85	17.08	19.68	22.4	23.26	21.64	18.98	15.58	13.86
3:00	12.44	12.54	13.65	15.02	17.45	20.12	22.94	23.73	21.79	18.93	15.42	13.77
4:00	12.29	12.36	13.43	14.85	17.25	19.88	22.69	23.45	21.62	18.75	15.27	13.63
5:00	12.15	12.19	13.25	14.69	17.06	19.72	22.51	23.26	21.47	18.61	15.14	13.5
6:00	12.22	12.34	13.33	14.76	17.05	19.68	22.65	23.48	21.56	18.72	15.18	13.62
7:00	12.11	12.26	13.22	14.7	17.1	19.9	22.7	23.39	21.44	18.62	15.1	13.56
8:00	12.27	12.39	13.4	15.35	18.44	21.48	24.05	24.3	21.8	18.73	15.21	13.66
9:00	11.87	11.82	12.84	14.86	17.46	20.26	22.93	23.54	21.48	18.31	14.61	13.19
10:00	12.81	13.15	14.25	15.84	18.4	21.21	23.96	24.7	22.74	19.82	15.91	14.08
11:00	14.28	14.33	15.19	16.62	19.15	21.95	24.72	25.53	23.64	20.75	16.99	15.39
12:00	13.85	13.89	14.45	15.62	18.01	20.58	23	23.68	22.43	19.65	16.51	14.54
13:00	14.48	14.5	14.98	16.04	18.42	21.02	23.48	24.14	22.85	20.05	17	15.07
14:00	14.87	14.88	15.33	16.31	18.68	21.34	23.84	24.45	23.09	20.25	17.27	15.39
15:00	14.48	14.4	15.08	16.27	18.6	21.22	23.62	24.03	22.7	19.92	17.01	15
16:00	14.48	14.4	15.08	16.27	18.59	21.25	23.67	24	22.63	19.79	16.88	14.91
17:00	14.23	14.19	14.91	16.13	18.41	21.09	23.49	23.78	22.36	19.45	16.53	14.58
18:00	14.87	14.91	15.54	16.74	18.95	21.68	24.07	24.41	23.01	20.34	17.27	15.43
19:00	14.13	14.25	14.94	16.19	18.41	21.08	23.48	23.72	22.28	19.64	16.63	14.77
20:00	13.6	13.67	14.15	15.36	17.56	20.19	22.55	22.75	21.5	19.07	16.21	14.4

Table 1. (*Continued*).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Local time	**Average daily temperature (°C)**											
21:00	13.67	13.93	14.93	16.22	18.59	21.4	23.94	24.34	22.53	19.78	16.47	14.7
22:00	13.26	13.48	14.46	15.7	18	20.73	23.23	23.76	22.02	19.4	16.13	14.37
23:00	12.95	13.1	14.06	15.26	17.47	20.11	22.61	23.23	21.59	19.04	15.82	14.12

Table 2. Irradiance per month and typical day, in local time (Source: PVGIS).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Local time	**Irradiance (W/m^2)**											
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	17	55	72	54	30	3	0	0	0
8:00	0	1	45	132	202	228	199	152	105	53	6	0
9:00	57	103	195	298	385	415	385	331	279	207	126	68
10:00	198	260	367	472	562	589	569	518	457	366	269	205
11:00	341	411	514	617	707	754	734	692	613	509	398	332
12:00	451	537	637	727	839	874	869	825	726	612	493	426
13:00	517	594	691	785	892	950	946	904	802	661	529	482
14:00	513	623	714	806	893	965	961	923	798	666	523	483
15:00	479	579	672	745	826	906	910	867	726	588	454	426
16:00	381	486	559	633	718	791	802	751	611	459	345	323
17:00	239	330	407	480	556	626	640	578	442	287	183	172
18:00	25	147	225	295	365	427	441	374	239	82	1	0
19:00	0	0	20	103	164	218	225	155	30	0	0	0
20:00	0	0	0	0	2	33	30	1	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0

3.1.3. End user's consumption profile

Any proposed PV installation should be adapted to the end user, whose needs are defined by their daily consumption curve. The daily consumption curves for the analysed period were downloaded by time bands from the e-distribution platform (EDISTRIBUCIÓN Redes Digitales, 2022).

3.1.4. Energy purchase and sale prices

The different prices of energy in the regulated market—PVPC DHA 2.0 purchase price, surplus self-consumption sale price for the simplified compensation mechanism

(PVPC) and the daily spot market price for Spain—were obtained from the REE information system (REE, 2022). The free-market purchase/sale costs were those indicated in each supplier's quotation.

3.1.5. Installation costs

Costs for the different installation components were calculated from data published online by different commercial companies, reviewed and further completed with labour and equipment costs per installation company with a market in the sector during 2020 of 100 kWp installed.

3.2. Results

The different quotes received for the purposes of this case study are summarized in **Table 3**.

Table 3. Photovoltaic installation company offer details.

	Company 1	Company 2	Company 3	Company 4
Installed kWp	2.22	4	1.22	2.1
Annual savings, €	337	*	349.39	706
Annual CO_2 reduction, kg	808	*	528	998
Cost + VAT, €	4999	7499	4413.81	4049
Amortization, years	13	*	13	6
Power, €/kWh	0.104229	0.114703	0.11	0.131
Period 1 energy, €/kWh	0.176	0.156103	0.11	0.1556
Period 2 energy, €/kWh	0.105	0.079641	0.08	0.1159
Surplus sales, €/kWh	0.07	0.04589	0.051	0.05
€/Wp	2.25	1.87	3.62	1.93

Note: *Data not provided.

Figure 3 shows PV production, electricity demand and purchase and sale prices in the regulated market depending on the chosen option, for each month and typical day.

Figure 4, which depicts solar radiation losses due to PV generator shading by adjacent buildings, shows a loss in production from 16:00 h in January, February, March, November and December, from 17:00 h in April and October and from 18:00 h in May, June, July, August and September. These losses imply an overall annual production loss of 7%–9%.

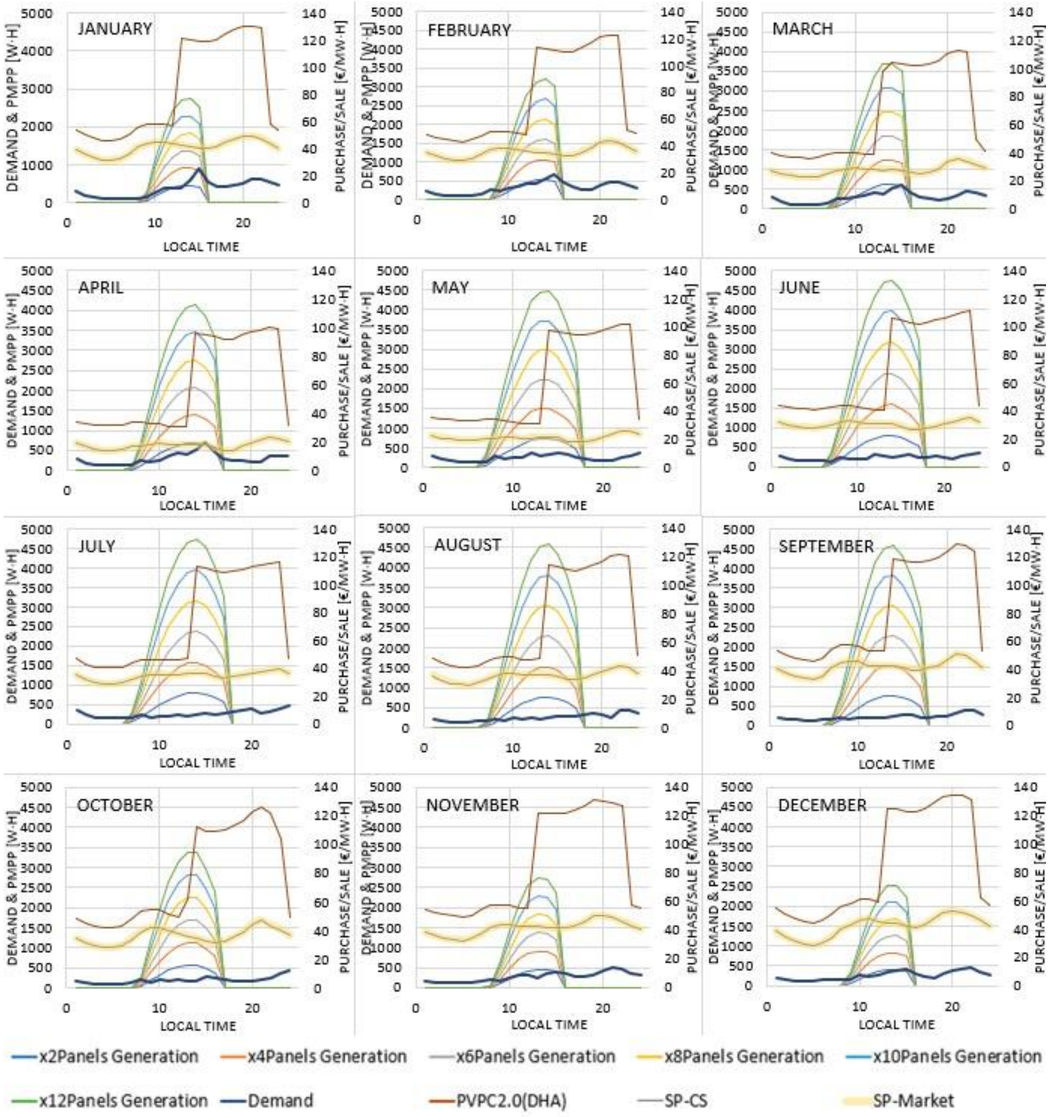

Figure 3. PV installation power production according to the number of panels: household electricity demand, PVPC DHA 2.0 electricity cost, sale price for simplified compensation and sale price for surplus sale to the market.

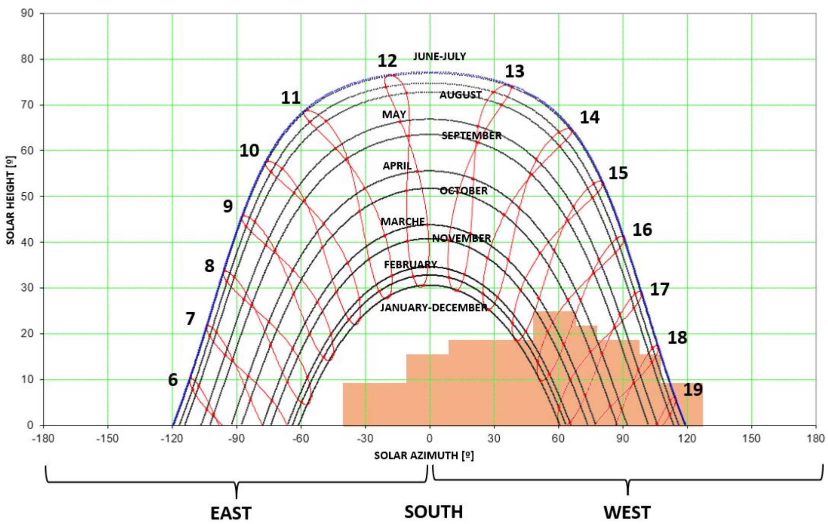

Figure 4. Solar radiation losses due to shading of the photovoltaic generator by adjacent buildings.

The installation costs as calculated in our case study are shown in **Table 4**.

Table 4. Total, fixed and variable costs according to installed peak power.

	1 kWp	2 kWp	3 kWp	4 kWp	5 kWp	6 kWp
Variable costs, €	1270.5	1754.5	2359.5	2964.5	3569.5	4174.5
Fixed costs, €	2825.35					
Total cost, €	4095.85	4579.85	5184.85	5789.85	6394.85	6999.85

Note: Fixed costs include the installation team, crane, direct current (DC) and alternating current (AC) protection boxes and the corresponding switchgear (DC circuit breakers, DC fuse holders, DC side transient overvoltage protection, 25A AC breaker, 25A/300 mA class A differential, and AC transient overvoltage protection), 20 m of 4-mm^2 DC cable + 20 mm solar shielding tubing, 20 m of 6-mm^2 AC cable + 20 mm solar shielding tubing, installation legalization and small-scale auxiliary material. Variable costs include the inverter, panels and roof support structure. Top brands supplied the material.

Figure 5 shows the linear regression function obtained from the point cloud (total cost, peak power), calculated using Equation (3).

$$C = 0.58771W_P + 3450.52 \tag{3}$$

where C is the total cost of the installation in €, and W_P is the installed peak power in W.

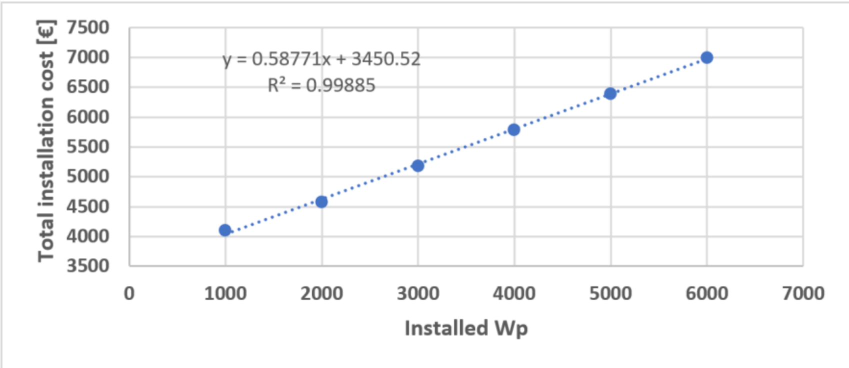

Figure 5. Installed power by total installation cost. Linear regression equation and Pearson's correlation coefficient.

Table 5 and **Figures 6** and **7** show results for annual cost savings, annual CO_2 reductions and straight-line amortization (defined as the number of years resulting from dividing the total installation cost by annual cost savings) for the simplified compensation and surplus sale to market systems.

Table 5. Total installation costs (including VAT), annual CO_2 reductions, annual savings and straight-line amortization for simplified compensation and surplus sale to market.

	Installation cost, €	Annual CO_2 reduction, kg	Annual savings, €		Straight-line amortization, years	
			Simplified compensation	Surplus to market	Simplified compensation	Surplus to market
1000 Wp	4095.85	217.46	168.28	162.04	24.34	25.28
2000 Wp	4579.85	434.92	232.40	215.47	19.71	21.25
3000 Wp	5184.85	652.38	257.31	263.07	20.15	19.71

Table 5. (*Continued*).

	Installation cost, €	Annual CO_2 reduction, kg	Annual savings, €		Straight-line amortization, years	
			Simplified compensation	Surplus to market	Simplified compensation	Surplus to market
4000 Wp	5789.85	869.34	277.99	309.87	20.83	18.68
5000 Wp	6394.85	1041.30	293.95	347.04	21.75	18.43
6000 Wp	6999.85	1157.46	300.11	373.35	23.32	18.75
Company 1	4999.00*	482.77	220.68	-	22.65	-
Company 2	7499.00*	869.35	239.69	-	31.29	-
Company 3	4413.81*	265.30	176.52	-	25	-
Company 4	4500.00*	456.67	126.48	-	35.58	-

Notes: Author's calculations, i.e., the calculations do not correspond to the data provided by the different companies, except for the installation costs indicated with an asterisk. The companies only supply installations for the simplified compensation system.

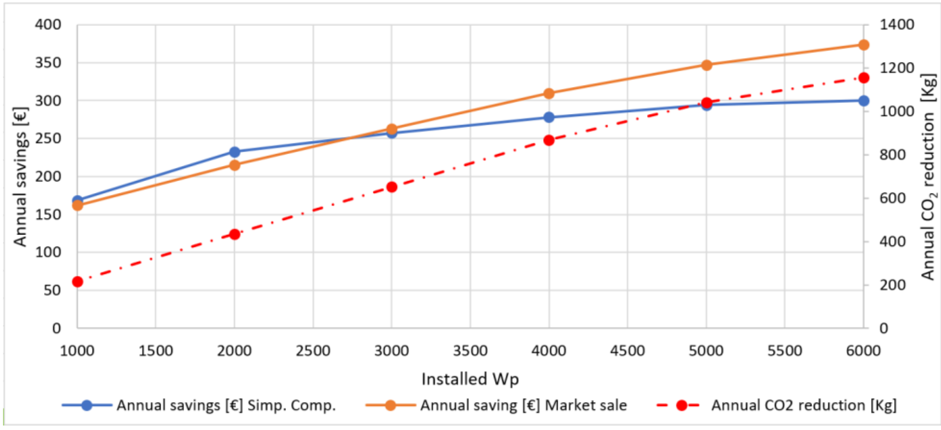

Figure 6. Annual cost savings and CO_2 reductions according to installed power for simplified compensation and surplus sale to the market.

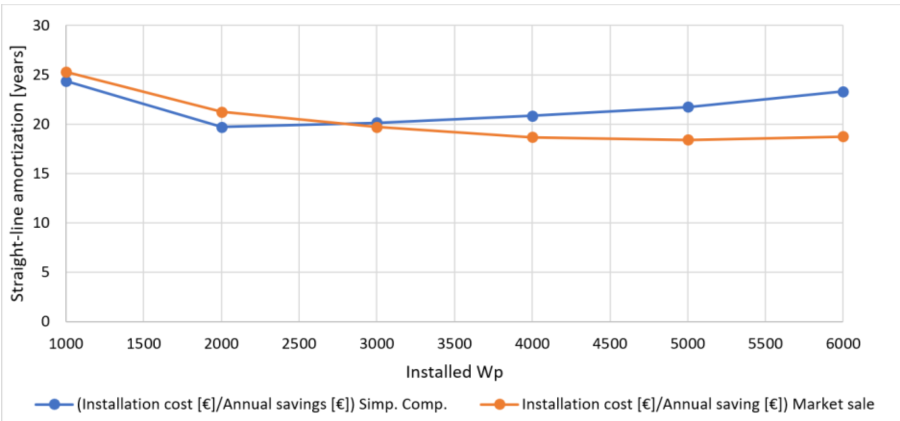

Figure 7. Photovoltaic installation straight-line amortization in years (total installation cost divided by annual cost savings) according to installed power for simplified compensation and surplus sale to the market.

Figures 8 and **9** depict analyses of the impact of DSM on annual savings and amortization for the simplified compensation and surplus sale to the market systems, respectively.

Figure 10 depicts the historical series that quantifies how electricity purchase and sale prices have evolved over time.

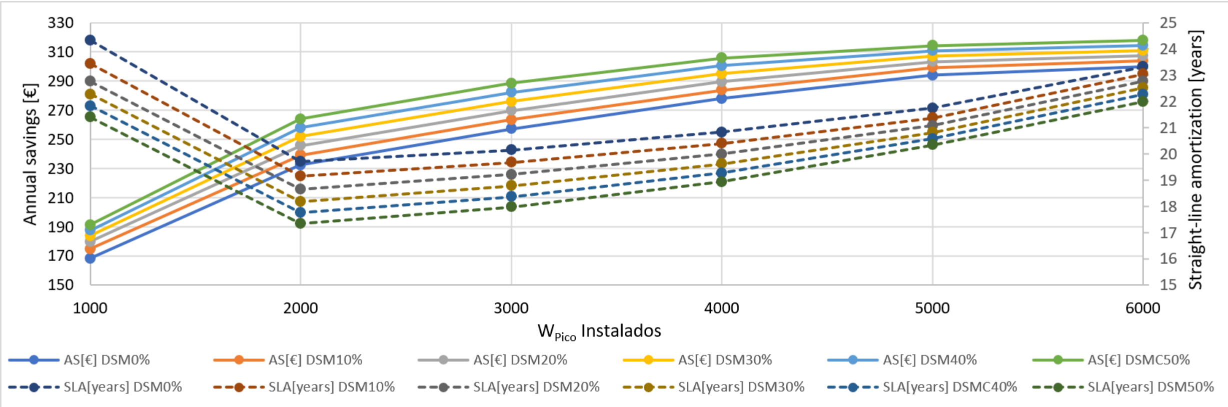

Figure 8. Impact of demand-side management on annual savings (AS) and straight-line amortization (SLA) period for simplified compensation in the regulated market.

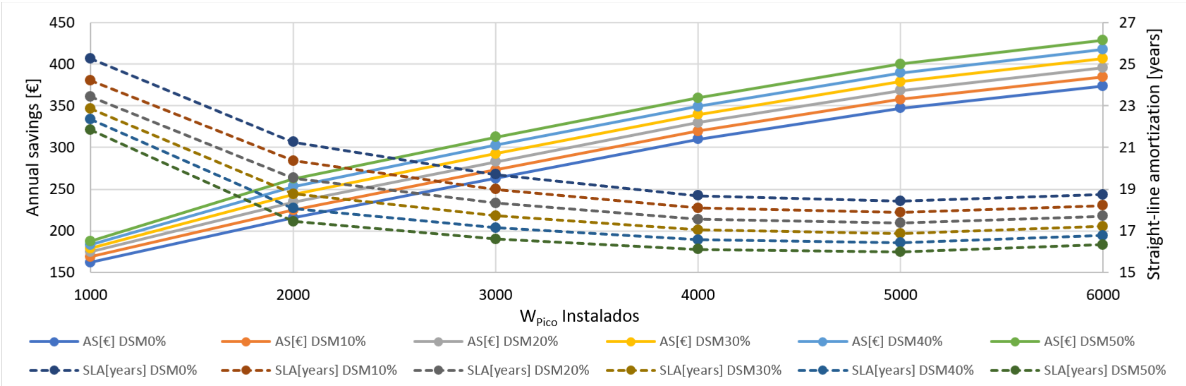

Figure 9. Impact of demand-side management on annual savings (AS) and straight-line amortization (SLA) period for surplus sale to the market.

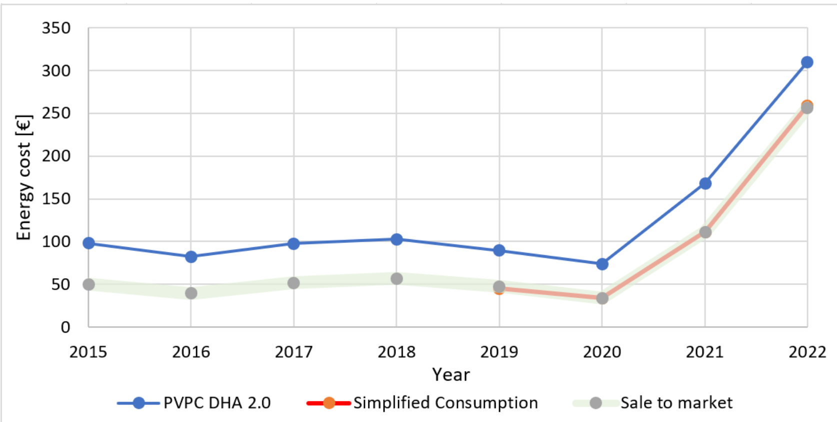

Figure 10. Historical electricity purchase and sale price series: annual mean PVPC DHA 2.0 values for simplified compensation and surplus sale to the market (Source: Red Eléctrica de España (REE)).

4. Discussion

RD 244/2019, in providing an important boost to renewable energies in Spain, has led to a proliferation of PV installations (**Figure 1**). Taking advantage of this new scenario, PV installation companies are offering PV installation kits for detached and semi-detached single-family homes, based on surplus energy purchase and sale prices for the simplified compensation mechanism.

Comparing the quoted costs (see **Table 2**) to the costs as calculated from Equation 3, the percentage dispersion was found to be in the range [−15.7%, 22.64%]. Only the installation proposed by company 4 was less expensive than calculated via Equation (3), i.e., 2.1 kWp at a cost of €4049. That company's panel guarantee was 12 years, compared to the 25 years for installations considered in Equation (3). The offers of the remaining companies were more expensive than the cost as calculated via Equation (3); for companies 1 and 3, the difference was only around 5%, while for company 2 (4 kWp at €7499), the cost was 22.64% greater.

The mean cost per Wp for our regression line (Equation 3) was €2.69/Wp, a value close to the €2.07/Wp proposed elsewhere (Prol and Steininger, 2017). The calculated values should be interpreted with care, however, since economies of scale can significantly affect this type of small-scale PV installation.

Despite warranty periods of 25 years and 10 years for the panels and the inverter, respectively, the calculated costs were based on a useful life of 25 years for the PV installation, during which it was assumed that the installation would not incur additional costs.

From an economic point of view, the results of this case study, as summarized in **Table 5** and **Figures 6** and **7**, show that, for simplified compensation (which only covers the energy cost, not associated charges), the best solution corresponds to an installation of just over 2 kWp (**Table 5** and **Figure 7**), as this pays for itself over approximately 20 years and achieves CO_2 emission reductions of approximately 430 kg/year (**Table 5** and **Figure 6**). However, for surplus sale to the market, the best solution corresponds to a 5 kWp installation (see **Table 5** and **Figure 7**), as it pays for itself over approximately 18 years and achieves CO_2 emission reductions of approximately 1026 kg/year (see **Table 5** and **Figure 6**).

Note that the household demand for electricity is likely to increase in the future as a result of new consumption requirements (electric cars, for instance), increased energy costs, the need for overall CO_2 emission reductions and the benefits afterward of the amortization period. Therefore, the best installation proposal is the option for surplus energy sale to the market, despite the drawbacks of a greater initial economic outlay and of administrative requirements regarding surplus returns to the market. Similar results as in our case study (5 kWp installed power, 41.01% self-consumption and 6.44 kW/day average consumption) have been reported by Hassan (2022): 7.15 kW optimal peak power and 41.93% self-consumption for an optimal angle and household average consumption of 7.42 kW/day.

The annual cost savings and CO_2 emission reductions indicated in the offers of the four companies significantly exceeded those obtained in this case study. In some cases, the difference in annual cost savings for a similar installed peak power was substantial (see company 1 and company 4 in **Table 2**). In other cases, there was a contradictory greater reduction in CO_2 emissions for a lower installed peak power (see company 1 and company 4 in **Table 2**). This would suggest that the offers did not fully contemplate losses due to shading, mismatch, dust, etc., and that the daily DSM profile was adjusted by shifting a representative percentage of consumption to the PV production period.

For both systems, DSM had a positive impact on annual costs savings (see **Figures 8** and **9**): the improvement range was [6%, 13.7%] for simplified compensation and [14.7%, 21.8%] for surplus sale to the market. These economic improvements were accompanied by a decreased amortization period of 1.3–2.9 years for simplified compensation and of 2.4–3.8 for surplus sale to the market.

Electricity costs increased very significantly between 2020 and March 2022. Switching from the PVPC DHA 2.0 tariff to the PVPC TD 2.0 tariff (discrimination in three periods defined according to the day of the week, time of day and geographical location) increased the average cost by 420%: 768% for simplified compensation and 756% for surplus sale to market. In this new scenario, for the optimal installation (5 kWp and surplus sale to the market), annual savings without and with DSM would be €1373.59 and €1507.74, respectively, resulting in straight-line amortization periods of 4.66 and 4.24 years, respectively.

5. Conclusion

Offers of PV installation companies do not seem to contemplate all possible losses in the PV energy generation process, and consumption profiles seem to be adjusted by shifting a percentage of demand to the PV production period.

For small-scale residential installations, economies of scale are relevant, as the installation costs for 1000 Wp and 5000 Wp range between €4.10/Wp and €1.28/Wp, respectively. Cost amortization (based on energy costs in 2020) is around 18-20 years depending on the option chosen regarding surpluses. Good DSM and subsidized installation costs would improve payback.

DSM contributes to improving annual cost savings in the range [6%, 21.8%] depending on the installed power and the option chosen regarding surpluses.

Our results suggest that, considering economies of scale and forecasts for the future, the offers received from the four companies are not optimal. The best offer was that for installation of 5 kWp with surplus sale to the market, a payback period 18 years and CO_2 emission reductions of 1026 kg/year. The surplus sale option, however, has the drawbacks of a greater initial outlay and more onerous administrative requirements.

From 2020 to March 2022, the average PVPC increase was 420%: 768% for simplified compensation and 756% for surplus sale to the market. The savings to be achieved in the new PVPC TD 2.0 tariff scenario for our optimal installation would be €1373.59 and €1507.74 for sale to the market of 50% of the contracted power without and with DSM, respectively, for amortization periods of 4.66 and 4.24 years, respectively.

The current self-consumption standard (RD 244/2019) represents an important advance in terms of renewable energy uptake in Spain. Of several options to manage surpluses, based on our analysis and energy costs, sale to the market is proposed as the only feasible mechanism for managing surpluses within the regulated market. This alternative should be accompanied by rules that facilitate administrative procedures offering guarantees to users.

Author contributions: Conceptualization, ENdG, LRPC, SPM and LMG; methodology, ENdG and LRPC; software, ENdG and FJOZ; validation, ENdG, and LRPC; formal analysis, ENdG; investigation, ENdG, FJOZ and LMG; resources, ENdG and LMG; data curation, ENdG; writing—original draft preparation, ENdG and SPM; writing—review and editing, ENdG; visualization, ENdG and LRPC; supervision, ENdG and LRPC; project administration, ENdG; funding acquisition, ENdG. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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