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Evaluating the Effect of Financing Costs on PV Grid Parity by Applying a Probabilistic Methodology

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Abstract: This paper presents a study that analyses the effect of financing costs on grid parity in photovoltaic (PV) installations by applying a probabilistic methodology. Three different case studies, located in Spain, have been considered, with 500 kW, 50 kW and 5 kW grid-connected PV generators. The technical and economic calculations were performed, considering the interest rate, yield across the Spanish geography, and PV module cost as parameters. The Monte Carlo method was applied to consider the full probabilistic range of values given to the different variables. The goal of this study was to determine, for the studied cases, the levelised cost of energy (LCOE) and the internal rate of return by considering realistic values of the variables. A success rate parameter was calculated, which determined the likelihood of the number of times that the LCOE was below the retail cost of electricity. All the cases were evaluated by applying 10,000 iterations, considering the standard deviations and means defined.

Keywords: photovoltaic (PV) tariffs; remuneration policies; grid parity

1. Introduction

When grid parity for photovoltaic (PV) installations is achieved, all the generated electrical energy can be sold at the same cost at which it is purchased from the grid [1]. To study properly how grid parity can be achieved, several aspects need to be taken into account, such as the possible subsidies or special economic regimes of the PV generators and the financing costs of this type of installation.

With regard to possible special economic subsidies or economic regimes of PV plants, as part of the ongoing challenge to achieve targeted carbon emission reductions set by European countries, governments in Europe introduced in some cases a mechanism for incentivising renewable energy production via the use of the feed-in tariff (FiT) [2]. From its introduction until now, the FiT has endured modifications with respect to political, economic, social and technological (PEST) matters. Due to the lucrative and stable nature of the FiT, private investors have deployed vast interest and investments [3]. The pricing structure that the FiT offers is vital in determining the growth rate of the PV industry and the investments made by private investors and the government, and therein lies the future of the industry [4]. It is important to note that PV is placed firmly as one of the most encouraged sources of energy generation [5], where profitability ratios, financial conditions, and the quantification of risks are all clearly defined [6]. This is most advantageous compared to the current fluctuating economy [7]. In addition, the inclusion of batteries can improve the profitability of grid-connected PV installations if the tariff policy allows optimising revenues by managing the charge and discharge of the batteries [8–11]. In the case of Spain, since the introduction of the FiT in 2007 [12], rising financial matters and the ever-changing energy policies have caused unreliability within the sector, hence causing Spain to revoke its FiT in 2012 [4]. Following the decision to revoke the FiT, energy consumption in Spain declined, leading to a significant electricity cost increase,

so that independent power generation became an attractive concept due to its financial savings and stability [1].

With regard to financing the costs of PV plants, the levelised cost of energy (LCOE) can be used to calculate the required system and finance expenses necessary to achieve grid parity [13,14]. It is important to keep in mind that financial costs have a significant influence on the LCOE calculation. To take into account the effect of financing costs, the risk of the investment [6] would have to be built into the interest rate [15]. The LCOE is not the same as the electricity cost, but it is used as a proxy for the total price paid by consumers while considering as many realistic costs as possible. When assessing LCOE against grid parity, all system and project costs should be taken into account. These costs include PV modules, structures, inverters, cables and installation.

In this paper, PV grid parity in Spain is studied, calculating the floor of the LCOE (worst-case scenario) for different cases and obtaining conclusions about the cost of the PV system and evaluating the effect of the financing costs [13] on PV grid parity.

In addition, the LCOE and internal rate of return (IRR) are calculated by using the Monte Carlo method [16], giving probabilistic ranges to all of the variables. This methodology allows us to obtain the probability of the possible scenarios. Other authors have used the Monte Carlo method to study a wide variety of realistic problems. The Monte Carlo method has been applied in several previous works in the field of renewable energy generation [17–19], where LCOE and IRR have been used as common economic evaluation tools. Therefore, the tools used in the work presented in this paper are appropriate because they are used routinely in previous work carried out by other authors, obtaining excellent results.

The approach and methodology shown in this work is completely new, as it allows an examination of the effect of financing costs on PV grid parity from a realistically point of view for a wide area (Spain in this case). The methodology used is easily applicable to other countries by adjusting the economic and energy parameters.

2. Materials and Methods

2.1. Costs of a Photovoltaic Installation

To obtain an accurate analysis, all system costs are kept up to date, as any variation can cause significant changes in the results. The total installed PV system cost includes the modules, inverter, support structure, electrical circuits and protections, the cables and structure anchor, as well as the engineering, the mechanical and electrical installation, and value-added tax (VAT).

It is important to note that the depreciation values of components are not considered except for solar modules, hence the costs of all other components are fixed except for that of PV modules. For this reason, in our probabilistic calculation the cost of each component, except the cost of the PV panels, is considered by means of a constant probability density function (PDF), where it changes depending on the three sizes of installation considered in this study (500 kW, 50 kW and 5 kW).

2.1.1. Solar Modules

In the past five years, the system costs decreased to as much as 25% of their initial cost [14]. From 2009 to 2014, the cost of the PV panels decreased by 75% [20]. In September 2012, the European Commission started an antidumping investigation into solar panel imports from China and their key components (wafers and cells). In international trade, dumping is defined as charging a lower price in an export market than is charged in the home country of the producer. It is seen as an anticompetitive strategy aimed at capturing market share in the export market using profits made in the domestic market. Companies that import directly from China, such as distributors, large-scale solar installers and investors, have to provide a bank guarantee for 11.8% of the customs-cleared value of the invoice from 6th June to midnight 5th August on all Chinese manufacturers, and between 37.3% and 67.9% from 6th August, dependent on the Chinese manufacturer [21]. Due to current antidumping

charges and legislation imposed by the European Union, it is not possible to assume a lower cost for Chinese-manufactured solar panels [22]. However, some manufacturers have moved factories out of the minimum import (MIP) cost area, and they are offering panels at a price below the MIP. So, the scenario considered in the present study of buying panels from these manufacturers is likely.

The size of the installation directly impacts the cost of the panels. As a result of our benchmark, in May 2015, the cost per W_p to install a 6 kW_p/5 kW_n (PV panel peak power/inverter nominal power: 6 kW peak/5 kW nominal) grid-connected PV system mounted on a rooftop was 3 €/W_p, and the cost of a single solar module was 1.5 €/W_p. The solar module cost for a single solar module was around 0.8 €/W_p in 2018. This means that the cost per W_p to install a 6 kW_p/5 kW_n grid-connected PV system mounted on a roof was below 2 €/W_p. For a 50 kW_p ground-mounted grid-connected PV system, the cost was 2 €/W_p, and the cost of a single solar module was 1 €/W_p. In 2018, the solar module cost was around 0.6 €/W_p. This means that the cost per W_p to install a 60 kW_p/50 kW_n grid-connected PV system mounted on a roof top is below 1.2 €/W_p. For a 500 kW_p ground-mounted grid-connected PV system, the cost was 1.5 €/W_p, and the cost of a single solar module was 0.8 €/W_p. In 2018, the solar module cost was set at 0.4 €/W_p, which means that the cost per W_p to install a 600 kW_p/500 kW_n grid-connected PV system on a rooftop was below 0.8 €/W_p.

The PDF used for the cost of solar modules is log-normal with a range between 1 €/kW_p and 0.2 €/kW_p, and, depending on the size of the installation (500 kW_n, 50 kW_n and 5 kW_n), the mean is determined by the costs described above, set as the current-day cost. The choice of this PDF is suitable for representing the cost of a power generation installation [18]. In this case, taking into account that we only consider uncertainty in the cost of the panels, it is logical to use this PDF to represent its cost.

2.1.2. Mounting Structures

The cost of mounting structures varies depending on the materials selected for the project, such as hot galvanised steel or aluminium. For example, aluminium structures were priced at 0.34 €/W_p. This cost has decreased by 50% over the past few years because aluminium was more than 50% cheaper in 2016 than in 2007 [23].

The cost of the mounting system is considered in our probabilistic calculation using a constant PDF, considered as fixed cost, where it depends on the three sizes of installation (500 kW, 50 kW and 5 kW).

2.1.3. Inverters

Solar inverters convert the DC energy generated from solar panels into AC electricity that is compatible with the AC voltage used in a home or business. A string inverter is the most common type of inverter in the market, and it is likely to be quoted by most small-to-medium-scale solar installation businesses. A microinverter is another type of inverter that is generally more expensive and not as common in the marketplace at the moment. The inverter selection is one of the most important aspects in any solar installation, and the cost of this component can be reduced if adequate analysis is made in selecting its correct size. For a 1 MW inverter, the market offers solutions of around 0.1 €/W. A quick market survey revealed a single inverter of 5 kW from a European manufacturer can be obtained at ~1200€, hence at a cost of 0.24 €/W_n.

The cost of the inverter was modelled using a constant PDF, and it was built into the installation costs. It changes across the three different cases (500 kW, 50 kW and 5 kW).

2.1.4. Operation and Maintenance

The operation and maintenance cost (OM) of an electric power generation system can generally be considered as the sum of a fixed part and a variable part, but in the case of PV installations the variable part can be considered equal to zero [24,25]. In this work the annual fixed OM costs are calculated by using Equation (1).

$$OM = 19.15 \cdot Peak Power \quad (1)$$

where the factor 19.15 has been estimated from the data published by the United States Department of Energy [24] and Fu et al. [25]. The units of this factor are €/kWp. This factor can be considered adequate, since it is based on economic studies of real PV installations [24,25]. *Peak Power* is the peak power of the PV system. The *OM cost* is modelled using a constant PDF, and it is built into the installation costs. It changes across the three different cases (500 kW, 50 kW and 5 kW).

2.2. Annual Energy Production

Before considering the peak power of the installation, the amount of electricity that can be produced by PV panels must be calculated. The amount of electricity produced by a panel is measured in kWh. These units are the same as the units on an electricity bill and are therefore directly comparable; the other unit that is often referred to when discussing output performance is the irradiation, which is the amount of energy from sunlight that hits the surface of a solar panel during a specified time. It is generally measured in kilowatt hours per square metre (kWh/m²). Irradiance is the power of the sunlight, usually measured in kW/m².

The PV panel power and, therefore, the PV system power (composed of several serial and/or parallel panels), is measured in terms of peak power using the unit Wp (watts of peak power), which is the power produced when the irradiance is 1 kW/m² in specific conditions. The nominal power of the PV system is usually considered as the nominal power of the inverter. Generally, the nominal power of the system (inverter power) is ~20% lower than the peak power of the system (peak power of the PV panels).

The PV array power is usually oversized relative to the inverter nominal power, achieving a lower cost of delivered energy (€/kWh), but if this DC-to-AC ratio is too high, then a significant amount of generated energy will be lost by clipping losses. When the DC input power of an inverter exceeds its AC output power, saturation losses occur (clipping losses). The ratio between the peak power of the panels and the nominal power of the inverter has been considered in this work is equal to 1.2, which is commonly recommended for the design of PV systems because it results in low clipping losses. Several studies verify that for values up to 1.2 the clipping losses are negligible [26,27]. On the other hand, grid-connected inverters usually have to work with a power factor equal to the unit [28,29], so the PV system only generates active power.

The annual energy production (*E*), in kWh, is calculated by Equation (2):

$$E = \text{Annual Yield} \cdot \text{Peak Power} \quad (2)$$

In Equation (2), *Annual Yield* is the annual energy generated by the PV system per kWp of peak power. This figure varies based on location, the tilt and azimuth angle of the panels and the sun-tracking system. For optimal tilt angle and no tracking system it varies from 1100 kWh/kWp in the north of Spain to 1500 kWh/kWp in the south of Spain. In this case, we define a whole range of annual yield from 1100 kWh/kWp to 1500 kWh/kWp. In our case, a fixed structure is considered, without trackers and with a tilt angle of the panel of 35° (average optimal tilt angle in Spain to maximise the total energy produced in the year). *Peak Power* is the peak power of the PV system. It is usually set as 20% more than the nominal power (inverter).

The PDF considered for the annual yield is a normal one with a range between 1100 and 1500 kWh/kWp. The mean is set at 1300 kWh/kWp, and from this set point the standard deviation is applied. This allows us to survey different locations between the ranges and to apply the annual yield throughout all the cases regardless of the power installed. Given this, we believe that we are representing a wider and realistic range of cases. This approach is applied for the three cases studied (500 kW, 50 kW and 5 kW). In Figure 1, the PDF for the yield used in this work can be observed.

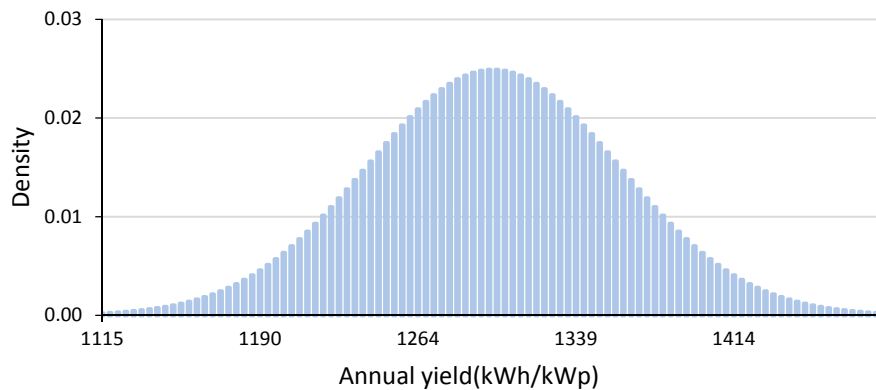


Figure 1. Probability density function (PDF) of the annual yield used in the Monte Carlo probabilistic method.

The use of this distribution is justified because sometimes some variables have a distribution that may not seem normal, this is usually due to the fact that the available historical data are not sufficient [17]. According to the central limit theorem [30], the distribution of a sample is approximately normal if the sample size is large enough. Therefore, in cases such as ours, where we wish to represent the probability density distribution of a variable that depends on multiple factors and is valid to represent the annual yield of the entire Iberian Peninsula, it is justified the use of a normal distribution. As confirmation that the choice of PDF is adequate, Killinger et al. [31] conducted a study that determined the distributions corresponding to the annual yield in several countries, and although differences between them are appreciable, it is observed that a normal distribution would be valid for all of them.

2.3. Economic Parameters Used in the Study

2.3.1. Levelised Cost of Energy

Different calculation methods can be used to determine the *LCOE* [14]. This is determined by the electricity remuneration system [32]. This work uses the Equation (3) [33] to calculate the *LCOE* (€/kWh):

$$LCOE = \frac{(\alpha \cdot I + OM)}{E} \quad (3)$$

where α . is the capital recovery factor, defined later in Section 2.3.2 (dimensionless parameter); *OM* is the annual operation and maintenance cost (€); *I* is the initial investment (€); and *E* is the annual energy production (kWh).

The *LCOE* drives our conclusions [16]. It is calculated depending on the interest rate (*r*), operation and maintenance (*OM*) cost and energy production (*E*). Therefore, it comprises all the variables and PDFs defined.

2.3.2. Capital Recovery Factor

In Equation (4), the simple Capital Recovery Factor calculation [33] is defined, which is a dimensionless parameter:

$$\alpha = \frac{r}{1 - (1 + r)^{-L}} \quad (4)$$

where *r* is the interest rate (percentage) and *L* is the lifetime of the system (years).

Obtaining a loan can be quite complicated in some countries like Spain (with relatively high interest rates of ~10%) [32]. Due to the financial issues encountered in Spain and the retroactive changes in the PV law over the past few years, the average interest rate rose to 10%. In this paper, the likely interest rates are considered at 6%. However, this figure is considered a variable parameter.

The interest rate is driven by a triangular PDF [18], with 4% being the lowest value and 12% the highest value. The mean would be 6% [4], where most of the loan cases provided by the banks are likely going to be. All this data has been extracted from online loan comparison research. The floor established is stated at 4% in the research, and it is very difficult to see values below this number. The maximum values have been established at 12% as values above that number are considered nonattractive (negative IRRs). Establishing the mean at 6%, the shape of the triangular PDF looks scalene, giving more cases above 4% than below [32]. For IRR calculation purposes, we consider the 12-year loan as standard.

In Figure 2, we can see the triangular PDF of the interest rate.

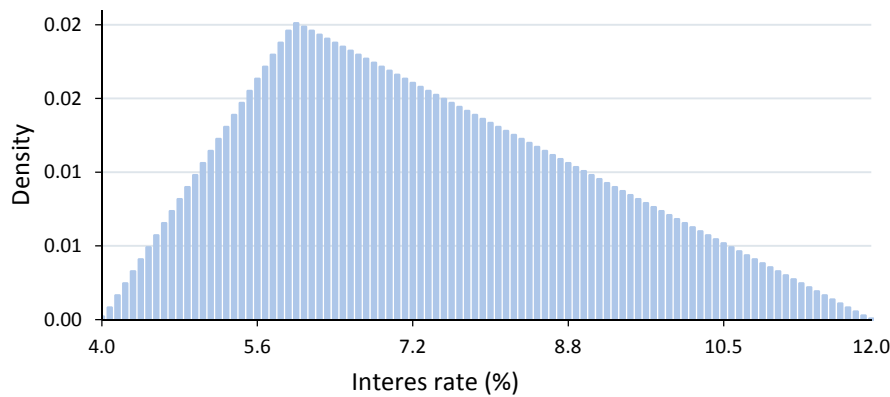


Figure 2. Probability density function (PDF) of the interest rate used in the Monte Carlo method.

Table 1 shows the capital recovery factor values calculated, manually, using Equation (4) for various interest rates. The lifetime of the system is 25 years.

Table 1. Capital Recovery Factor calculation.

Interest rate (%)	12	10	8	6	4
Recovery factor (α)	0.1275	0.1102	0.0937	0.0782	0.0640

The value of the Capital Recovery Factor varies depending on the interest rate (r). The latter applies to the three cases studied, as the PDF of the financial cases are the same regardless of the system power and the energy production.

Applying the Monte Carlo method and using the triangular PDF of the interest rate (Figure 2), we obtained the histogram corresponding to the recovery factor shown in Figure 3. We calculated 10,000 iterations.

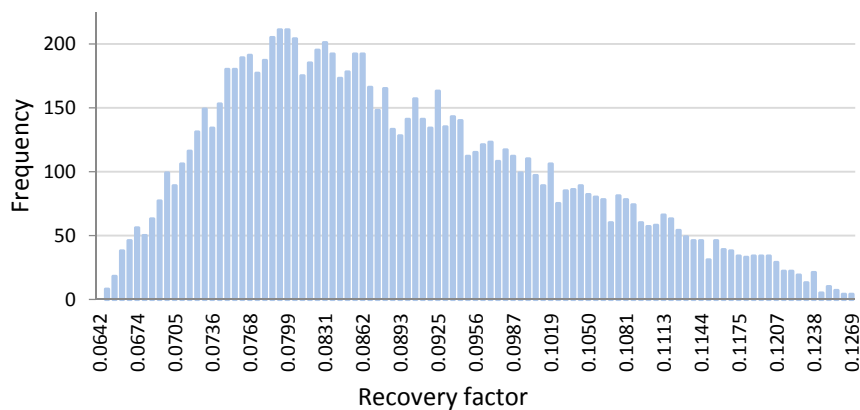


Figure 3. Histogram of the annual recovery factor used in the Monte Carlo method.

A summary of the PDFs of all the variables described previously is shown in Table 2.

Table 2. PDFs used in the Monte Carlo calculation.

Inputs	PDF	Range	Unit
Power	Constant value	6–600	kWp
Lifetime of the system	Constant value	25	Years
Annual Yield	Normal	1100–1500	kWh/kWp
Capital expenditure	Log-normal	0.2–1	€/Wp
Interest rate	Triangular	4–12	%
Retail cost	Constant	0.174	€/kWh

Because the model used in this work is based on the FiT, the lifetime of the project was assumed to be 25 years, as this also coincides with the modules' 25-year warranties.

Table 3 presents the initial investments required in construction of a 6 kWp PV system (5 kW nominal power), considering all system losses.

Table 3. Cost of a PV system at 6000 Wp (5000 W inverter).

	PV Module Cost (€/Wp)				
	1	0.8 *	0.6	0.4	0.2
PV module (6 kWp)	6000	4800	3600	2400	1200
Fixed installation costs	6780	6780	6780	6780	6780
TOTAL PV installed cost (€)	12,780	11,580	10,380	9180	7980
VAT (21%)	2684	2432	2180	1928	1676
TOTAL PV installed cost, including taxes (€)	15,464	14,012	12,560	11,108	9656
Total specific cost (€/Wp)	2.58	2.34	2.09	1.85	1.61
Total specific cost (€/W)	3.09	2.80	2.51	2.22	1.93

* Current case.

2.3.3. Internal Rate of Return

The *IRR* is a metric used in the capital budget to estimate the profitability of the potential investments [34]. The *IRR* is a discount rate that makes the net present value (*NPV*) [35] of all cash flows of a project zero [15].

The *IRR* with a loan is much higher than the *IRR* without a loan because a loan at a relatively low interest rate favours the *IRR*. The *IRR* with a loan assumes that the project has a financing scheme typical of the PV industry [4].

The *IRR* calculation procedure is based on determining which *IRR* value results in the *NPV* being zero, as shown in Equation (5):

$$NPV = \sum_{t=1}^n \frac{F_t}{(1 + IRR)^t} - I = 0 \quad (5)$$

where F_t is the cash flow during the year t , n is the number of years of the investment and I is the initial investment (€).

The *IRR* was calculated using the interest rate (r), operation and maintenance (OM) cost, annual energy production (E), tax rate (20%) and loan length (12 years), therefore it comprises all the variables and PDFs defined previously.

The sale price of energy was considered equal to the regulated tariff for low-power consumers, in Spain, who do not want to negotiate with the manufacturers. In this work we assumed a regulated tariff of 17.4 c€/kWh, including taxes [1].

3. Results

The cases studied are based on the different annual yields that Spain has, which fit in a range between 1100 and 1500 kWh/kWp. The power of the generator is another variable used as the scaled economy impacts directly on the cost of the panels and installation, which means the grid parity point is affected. Cases of 5 kW, 50 kW and 500 kW of nominal power are considered.

3.1. 5 kW Case Study

First, the deterministic calculation of the LCOE was performed (without considering the PDFs). Thus, it was possible to obtain the most unfavourable case for all the variables that can be used to perform a sensitivity analysis. The aim of this calculation, considering pessimistic values, was to set a conservative scenario that can define a minimum value for the LCOE.

Table 3 shows the costs and taxes, previously described, for a 5 kW system.

The fixed costs used are the support structure, priced at 1700 €; inverter, priced at 1200 €; electrical circuits and protections, priced at 800 €; other materials (cables, anchor and so on), priced at 500 €; mechanical installation, priced at 1620 €; and electrical installation and engineering, priced at 960 €. All of these fixed installation costs total 6780 €.

In Table 3, five case studies are considered; four of them are theoretical and one is a practical case. The cost at 0.8 €/Wp is the current scenario. Although the market could raise its panel costs, the market tendency shows a continuous cost reduction and reaches the other theoretical scenarios shown in Table 1 at costs of 0.6 €/Wp, 0.4 €/Wp and 0.2 €/Wp. Nevertheless, the scenario of 1 €/Wp was also considered.

3.1.1. Levelised Cost of Energy (LCOE)—Calculation Method Analysis for 5 kW and 1100 kWh/kWp Cases

Introducing all the previous parameters and fixing the regulated tariff at 17.4 c€/kWh including taxes and with a fixed interest rate of 10% produces the following results (Table 4), considering an energy production of 6600 kWh/yr, OM annual costs of 114.9 € and a lifetime for the installation of 25 years. The recovery factor value results as 0.1102.

Table 4. Comparison of levelised cost of energy (LCOE) and internal rate of return (IRR) based on a recovery factor at 10% interest, for the 5 kW case.

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)	IRR (%)
1	15,464	0.2756	−4.811
0.8	14,012	0.2514	−3.83
0.6	12,560	0.2271	−2.68
0.4	11,108	0.2029	−1.31
0.2	9656	0.1787	0.40

With the results obtained for the LCOE, it can be concluded that Spain would reach grid parity under conditions where the PV modules cost below 0.2 €/Wp. However, the IRR calculated at 25 years with a standard loan of 10% reaches positive values at 0.2 €/Wp. This is because inflation affects the retail electricity cost and changes the LCOE along with time, from beyond to above.

Figure 4 illustrates a clear presentation of the point at which the retail costs and generation costs reach an equilibrium. As we can see, a considerable deviation affects the grid parity forecast.

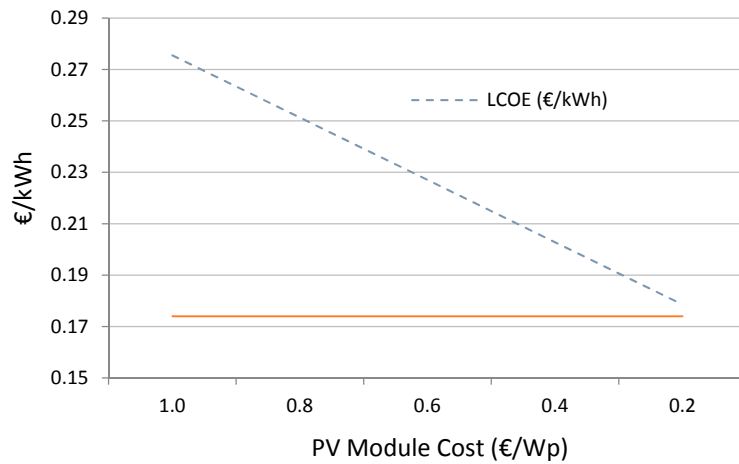


Figure 4. Analysis of the levelised cost of energy (LCOE) against the retail electricity cost at a fixed interest rate of 10% (5000 W inverter, deterministic method).

This case was analysed by introducing a sensibility analysis based on different interest rates to determine which loan terms and conditions allow the system to achieve the retail electricity cost target for grid parity for a different module cost (€/Wp), as shown in Table 5. The positions where the LCOE is lower than the retail cost of energy have been highlighted.

Table 5. LCOE over a range of interest rates (5000 W inverter, deterministic method).

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)					
		Interest Rate (%):	12	10	8	6	4
1.0	15,464		0.3161	0.2755	0.2369	0.2007	0.1674
0.8	14,012		0.2881	0.2513	0.2163	0.1835	0.1533
0.6	12,560		0.2600	0.2270	0.1957	0.1663	0.1392
0.4	11,108		0.2320	0.2028	0.1751	0.1491	0.1251
0.2	9656		0.2039	0.1786	0.1545	0.1318	0.1110

Figure 5 shows a graphical representation of the Table 5 results against the retail cost of electricity.

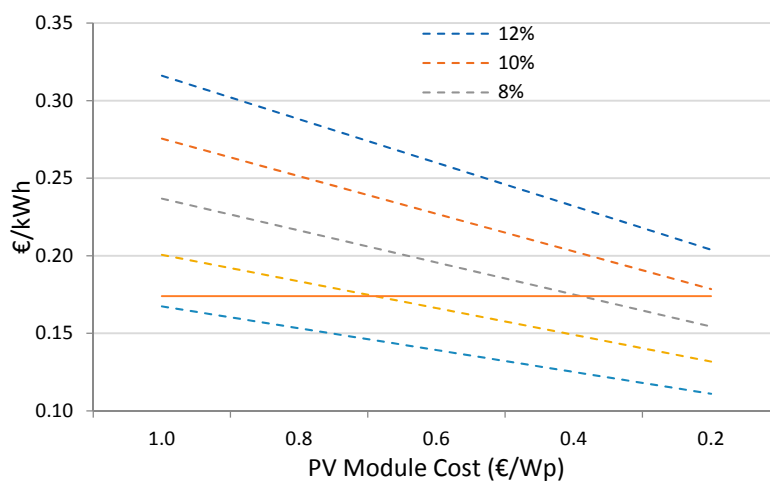


Figure 5. Analysis of the LCOE against the retail electricity cost at various interest rates (5000 W inverter, deterministic method).

3.1.2. 5 kW Case Study Sensibility Analysis

For the 5 kW case study a sensibility analysis was performed considering a range of annual yields from 1100 to 1500 kWh/kWp with a step of 100 kWh/kWp in the range. Using the methodology applied in Section 3.1.1, it is possible to calculate the LCOE by considering the method described previously, fixing the regulated tariff at 17.4 c€/kWh including taxes and with a fixed interest rate of 10%.

Table 6 shows the most relevant results for the five cases. Case 1 corresponds to 1100 kWh/kWp and Case 5 corresponds to 1500 kWh/kWp. The positions where the LCOE is lower than the retail cost of energy have been highlighted.

Table 6. Comparison of the LCOE based on the different annual yield for 5 kW (deterministic method).

PV Module Cost (€/Wp)	System Cost (€)	Annual Yield (kWh/kWp):	LCOE (€/kWh)				
			Case 1 1100	Case 2 1200	Case 3 1300	Case 4 1400	Case 5 1500
1.0	15,464		0.276	0.254	0.236	0.220	0.207
0.8	14,012		0.251	0.232	0.215	0.201	0.189
0.6	12,560		0.227	0.210	0.195	0.182	0.171
0.4	11,108		0.203	0.187	0.174	0.163	0.153
0.2	9656		0.179	0.165	0.154	0.144	0.136

Five case studies are considered in Table 3, but we consider the cost at 0.8 €/Wp as the current scenario. For that reason, the PDF for the panel cost is log-normal with a mean of 0.8 (€/Wp) and a standard deviation of 0.2 (€/Wp). The panel cost floor is set at 0.2 (€/Wp) so that 95% of the cases are represented in the PDF (Figure 6).

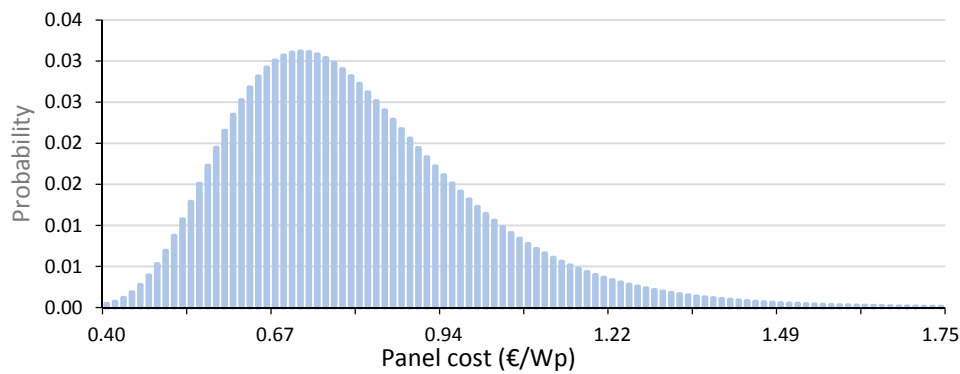


Figure 6. PDF of panel cost for a 5 kW system.

Introducing all the variables in the probabilistic analysis with the Monte Carlo method delivers a wide range of results, giving the following representation (Figure 7), with the frequency of the LCOE above and below the retail electricity cost.

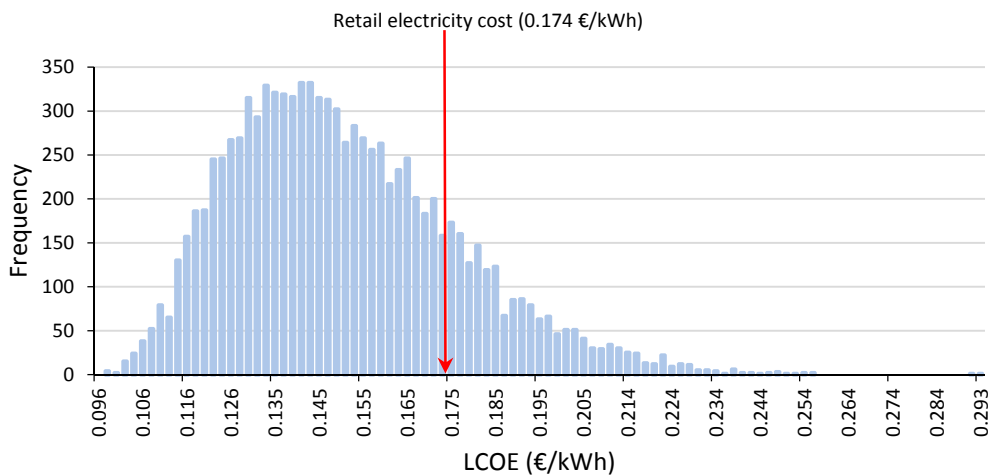


Figure 7. Histogram of the LCOE calculated with the Monte Carlo method for a 5 kW system.

Introducing the results of the iterations given by the Monte Carlo method for the business model, we obtain the IRR values. The IRR results for the 5 kW business case are shown graphically in Figure 8.

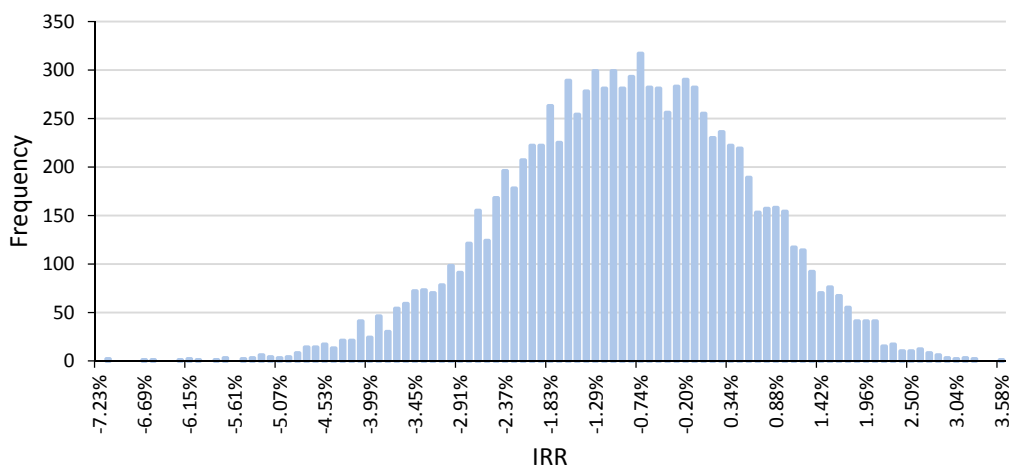


Figure 8. Histogram of the internal rate of return (IRR) calculated with the Monte Carlo method for a 5 kW system.

A success rate parameter (%) is introduced by counting the number of iteration results below the retail cost of the electricity and dividing by the total number of iterations (10,000). By analysing the frequency of the results and the value itself, the success rate can be calculated for each case. In the case of a 5 kW installation, the success rate would be 82.26%. This means that in 82.26% of cases, grid parity is achieved, as the LCOE is lower than the retail cost. However, as a business case, the mean of the IRR is negative (−0.97%). Therefore, it can be concluded that the loan input in the model contributes negatively to the success of the investment.

3.2. 50 kW Case Study

The manual calculation of the LCOE takes the worst-case scenario to set a conservative scenario that can define a floor. In Table 7 below, the fixed costs are represented (variable costs and taxes described in previous points) for a 50 kW system.

Table 7. Cost of a PV system at 60,000 Wp (50,000 W inverter).

	PV Module Cost (€/Wp)				
	1	0.8	0.6 *	0.4	0.2
PV module (60 kWp)	60,000	48,000	36,000	24,000	12,000
Fixed installation costs	38,000	38,000	38,000	38,000	38,000
TOTAL PV installed cost (€)	98,000	86,000	74,000	62,000	50,000
VAT (21%)	20,580	18,060	15,540	13,020	10,500
TOTAL PV installed cost, including taxes (€)	118,580	104,060	89,540	75,020	60,500
Total specific cost (€/Wp)	1.98	1.73	1.49	1.25	1.01
Total specific cost (€/W)	2.37	2.08	1.79	1.50	1.21

* Current case.

The fixed costs used are the support structure, priced at 9000 €; inverter, priced at 8000 €; electrical circuits and protections, priced at 2000 €; other materials (cables, anchor and so on), priced at 5000 €; mechanical installation, priced at 6000 €; and electrical installation and engineering, priced at 8000 €. These fixed installation costs come to a total of 38,000 €.

A worst-case scenario can be assumed for a 50 kW system as shown in Table 7 [4].

Five case studies are considered in Table 7: four of them are theoretical and one is a practical case. The cost at 0.6 €/Wp is the current scenario. Although the market could raise its panel costs, the market tendency shows a continuous cost reduction and reaches the other theoretical scenarios shown in Table 7 at costs of 0.4 €/Wp and 0.2 €/Wp. The scenarios of 0.8 €/Wp and 1 €/Wp are also considered.

3.2.1. LCOE—Calculation Method Analysis for 50 kW and 1100 kWh/kWp Case

Introducing all the previous parameters and fixing the regulated tariff at 17.4 c€/kWh including taxes and with a fixed interest rate of 10% produces the following results (Table 8), considering an energy production of 60,600 kWh/yr, OM annual costs of 1149 € and a lifetime for the installation of 25 years. The recovery factor value results as 0.1102.

Table 8. Comparison of LCOE and IRR based on a recovery factor at 10% interest for the 50 kW case.

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)	IRR (%)
1	118,580	0.2154	−2.049
0.8	104,060	0.1911	−0.53
0.6	89,540	0.1669	1.39
0.4	75,020	0.1427	3.97
0.2	60,500	0.11841	7.46

With the results obtained for the LCOE, it can be concluded that Spain would reach grid parity under conditions where the PV modules cost between 0.8 €/Wp and 0.6 €/Wp. The IRR calculated at 25 years with a standard loan of 10% reaches positive values at between 0.8 €/Wp and 0.6 €/Wp. It is concluded that there is a floor of 1.39% of IRR for the current panel cost scenario and the worst-case scenario of yield and interest rate.

Figure 9 illustrates a clear presentation of the point at which the retail costs and generation costs reach an equilibrium. As can be seen, there is a considerable deviation which impacts the grid parity forecast.

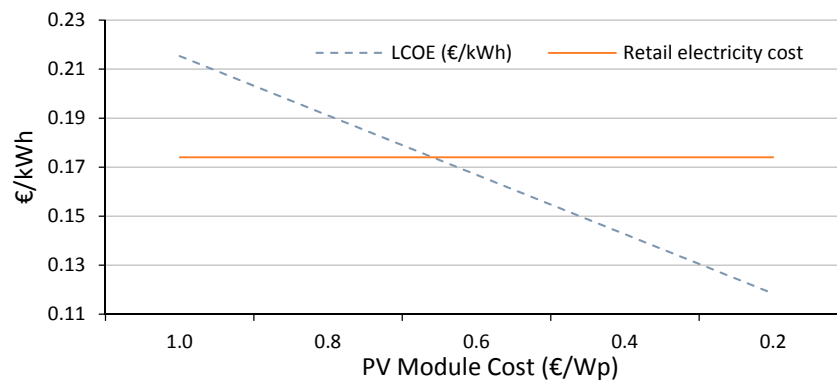


Figure 9. Analysis of the LCOE against the regulated tariff at a fixed interest rate of 10% (50,000 W inverter, deterministic method).

This case is analysed by introducing a sensibility analysis based on different interest rates, determining which loan terms and conditions allow the system to achieve the regulated tariff target for grid parity for a different module cost (€/Wp), as shown in Table 9. The positions where the LCOE is lower than the retail cost of energy have been highlighted

Table 9. LCOE over a range of interest rates (50,000 W inverter, deterministic method).

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)					
		Interest Rate (%):	12	10	8	6	4
1.0	118,580		0.2465	0.2153	0.1857	0.1579	0.1324
0.8	104,060		0.2184	0.1911	0.1651	0.1407	0.1183
0.6	89,540		0.1904	0.1669	0.1445	0.1235	0.1042
0.4	75,020		0.1623	0.1426	0.1239	0.1063	0.0902
0.2	60,500		0.1343	0.1184	0.1033	0.0891	0.0761

Figure 10 shows a graphical representation of the Table 9 results against the retail electricity cost.

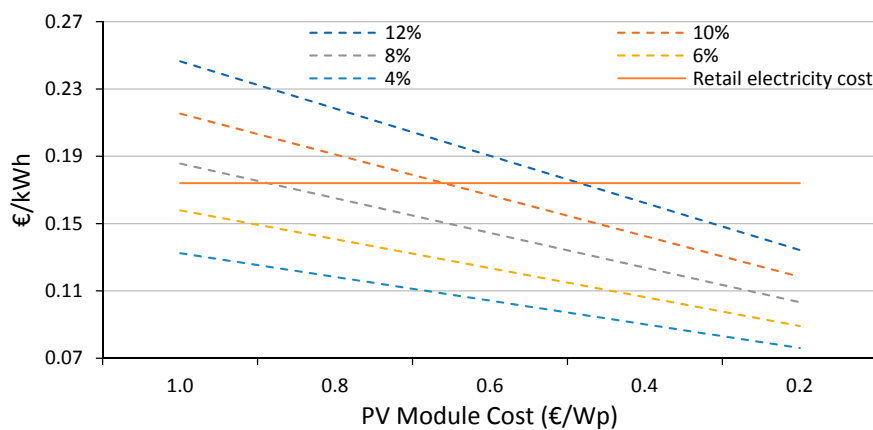


Figure 10. Analysis of the LCOE against the retail electricity cost at various interest rates (50,000 W inverter, deterministic method).

3.2.2. 50 kW Case Study Sensibility Analysis

For the 50 kW case study a sensibility analysis has been performed considering a range of annual yields from 1100 to 1500 kWh/kWp with a step of 100 kWh/kWp in the range. Using the methodology applied in Section 3.1.1, it is possible to calculate the LCOE considering the method

described previously, fixing the regulated tariff at 17.4 c€/kWh including taxes and with a fixed interest rate of 10%.

Table 10 shows the most relevant results for the five cases. Case 1 corresponds to 1100 kWh/kWp and Case 5 corresponds to 1500 kWh/kWp. The positions where the LCOE is lower than the retail cost of energy have been highlighted.

Table 10. Comparison of the LCOE based on the different annual yield for 50 kW.

PV Module Cost (€/Wp)	System Cost (€)	Annual Yield (kWh/kWp):	LCOE (€/kWh)				
			Case 1 1100	Case 2 1200	Case 3 1300	Case 4 1400	Case 5 1500
1.0	118,580		0.215	0.199	0.185	0.173	0.163
0.8	104,060		0.191	0.177	0.164	0.154	0.145
0.6	89,540		0.167	0.154	0.144	0.135	0.127
0.4	75,020		0.143	0.132	0.123	0.116	0.109
0.2	60,500		0.118	0.110	0.103	0.097	0.091

Five case studies are considered in Table 7, but the cost at 0.6 €/Wp is considered as the current scenario. For that reason, the PDF for the panel cost is log-normal with a mean of 0.6 (€/Wp) and a standard deviation of 0.2 (€/Wp). The panel cost floor is set at 0.2 (€/Wp) so that the 95% of the cases are represented in the PDF (Figure 11).

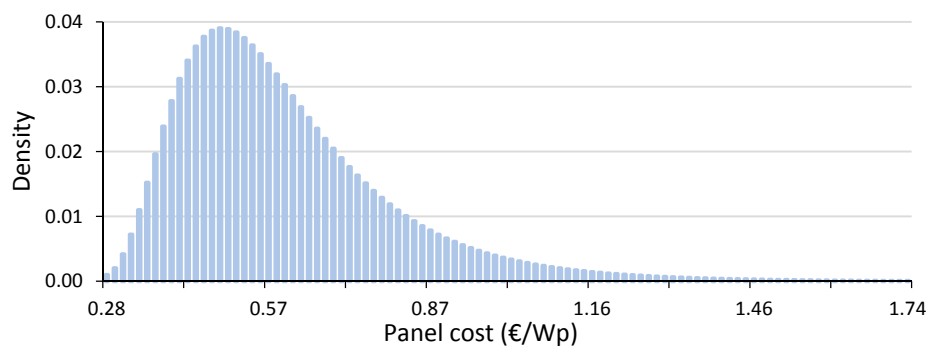


Figure 11. PDF of panel cost for a 50 kW system.

Introducing all the variables in the probabilistic analysis with the Monte Carlo method delivers a wide range of results, giving the following representation (Figure 12) with the frequency of the LCOE above and below the retail electricity cost.

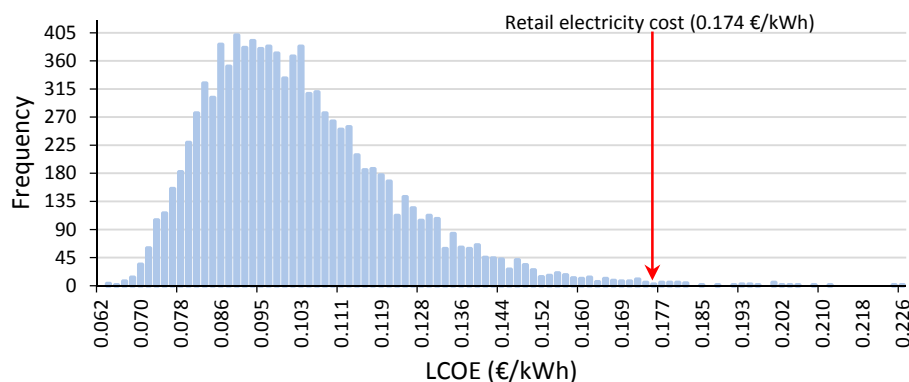


Figure 12. Histogram of the LCOE calculated with the Monte Carlo method for a 50 kW system.

Introducing the results of the iterations given by the Monte Carlo method for the business model, we obtain the IRR values. The IRR results for the 50 kW business case are shown graphically in Figure 13.

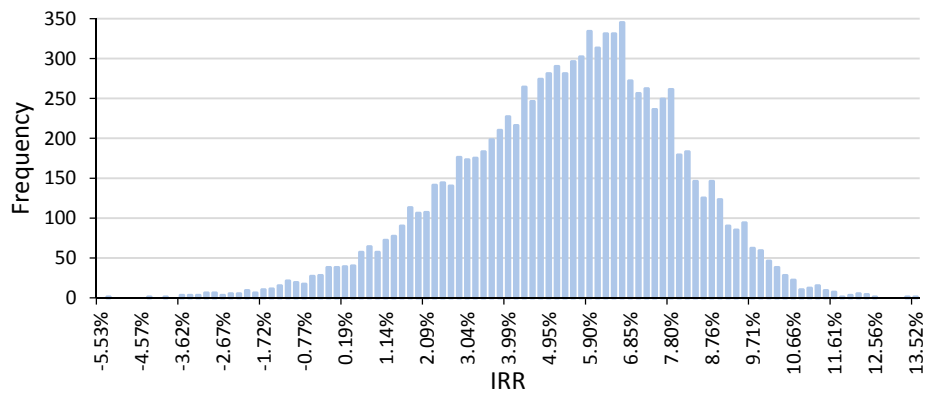


Figure 13. Histogram of the IRR calculated with the Monte Carlo method for a 50 kW system.

A success rate parameter (%) is introduced by counting the number of iteration results below the retail cost of the electricity and dividing by the total number of iterations (10,000). Analysing the frequency of the results and the value itself, the success rate for each case can be calculated. In this case of a 50 kW installation, it can be concluded that the success rate would be 99.59%. This means that in 99.59% of cases, grid parity is achieved as the LCOE is lower than the retail cost. As a business case, the mean of the IRR is positive (5.29%). Therefore, it can be concluded that even though the loan input in the model contributes negatively, the investment is successful.

3.3. 500 kW Case Study

The manual calculation of the LCOE takes the worst-case scenario for all the variables that could influence the sensitivity analysis carried out on this section. The aim of this calculation, considering pessimistic values, is to set a conservative scenario that can define a floor. The table below (Table 11) represents the fixed costs, variable costs and taxes, described in previous points, for a 500 kW system.

Table 11. Cost of a PV system at 600,000 Wp (500,000 W inverter).

	PV Module Cost (€/Wp)				
	1	0.8	0.6	0.4 *	0.2
PV module (600 kWp)	600,000	480,000	360,000	240,000	120,000
Fixed installation costs	245,000	245,000	245,000	245,000	245,000
TOTAL PV installed cost (€)	980,000	725,000	605,000	485,000	365,000
VAT (21%)	177,450	152,250	127,050	101,850	76,650
TOTAL PV installed cost, including taxes (€)	1,022,45	877,250	732,050	586,850	441,650
Total specific cost (€/Wp)	1.70	1.46	1.22	0.98	0.74
Total specific cost (€/W)	2.04	1.75	1.46	1.17	0.88

* Current case.

Fixed costs: support structure, priced at 90,000 €; inverter, priced at 40,000 €; electrical circuits and protections, priced at 40,000 €; other materials (cables, anchor and so on), priced at 20,000 €; mechanical installation, priced at 45,000 €; and electrical installation and engineering, priced at 10,000 €. These fixed installation costs come to a total of 245,000 €.

A worst-case scenario can be assumed for a 500 kW system as shown in Table 11 [4].

As we have done previously, five case studies are considered in Table 11: four of them are theoretical and one is a practical case. The cost at 0.4 €/Wp is the current scenario. Although the

market could raise its panel costs, the market tendency shows a continuous cost reduction and reaches the other theoretical scenarios shown in Table 11, especially at costs of 0.2 €/Wp; the scenarios of 0.6 €/Wp, 0.8 €/Wp and 1 €/Wp are also considered.

3.3.1. LCOE—Calculation Method Analysis for 500 kW and 1100 kWh/kWp Case

Introducing all the previous parameters and fixing the regulated tariff at 17.4 c€/kWh, including taxes and with a fixed interest rate of 10%, produces the following results (Table 12), considering an energy production of 660,000 kWh/yr, OM annual costs of 11,490€ and a lifetime for the installation of 25 years. The recovery factor value is 0.1102.

Table 12. Comparison of LCOE and IRR based on a recovery factor at 10% interest, for the 500 kW case.

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)	IRR (%)
1	1,022,45	0.1585	−0.316
0.8	877,250	0.1385	1.67
0.6	732,050	0.1184	4.36
0.4	586,850	0.0984	8.02
0.2	441,650	0.07834	14.52

With the results obtained for the LCOE, it can be concluded that Spain would reach grid parity under all conditions represented in this paper. However, the IRR calculated at 25 years with a standard loan of 10% reaches positive values between 1 €/Wp and 0.8 €/Wp. It can be concluded that there is a floor of 8.02% of IRR for the current panel cost scenario (0.4 €/Wp) and the worst-case scenario of yield and interest rate.

Figure 14 illustrates a clear presentation of the point at which the retail costs and generation costs reach an equilibrium. As can be seen, there is a considerable deviation impacting the grid parity forecast.

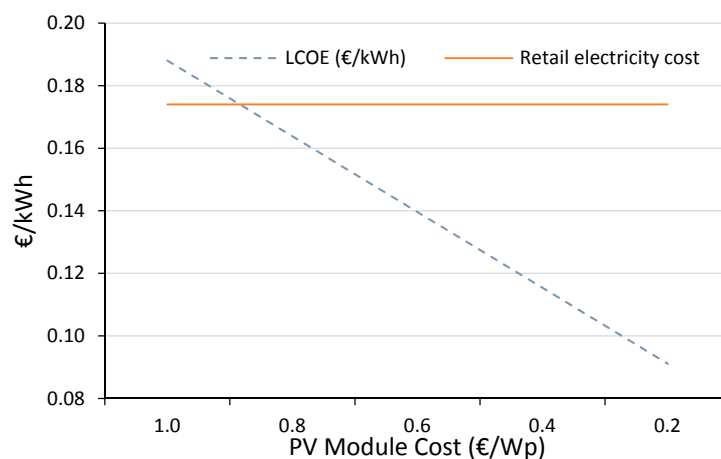


Figure 14. Analysis of the LCOE against the retail electricity cost at a fixed interest rate of 10% (500,000 W inverter, deterministic method).

This case is analysed by introducing a sensibility analysis based on different interest rates, determining which loan terms and conditions allow the system to achieve the regulated tariff target for grid parity for a different module cost (€/Wp), as shown in Table 13. The positions where the LCOE is lower than the retail cost of energy have been highlighted.

Table 13. LCOE over a range of interest rates (50,000 W inverter, deterministic method).

PV Module Cost (€/Wp)	System Cost (€)	LCOE (€/kWh)					
		Interest Rate (%):	12	10	8	6	4
1.0	1,022,450		0.2149	0.1881	0.1625	0.1386	0.1166
0.8	877,250		0.1869	0.1638	0.1419	0.1214	0.1025
0.6	732,050		0.1588	0.1396	0.1213	0.1042	0.0884
0.4	586,850		0.1308	0.1154	0.1007	0.0870	0.0743
0.2	441,650		0.1027	0.0911	0.0801	0.0697	0.0602

Figure 15 shows a graphical representation of the Table 13 results against the retail cost of electricity.

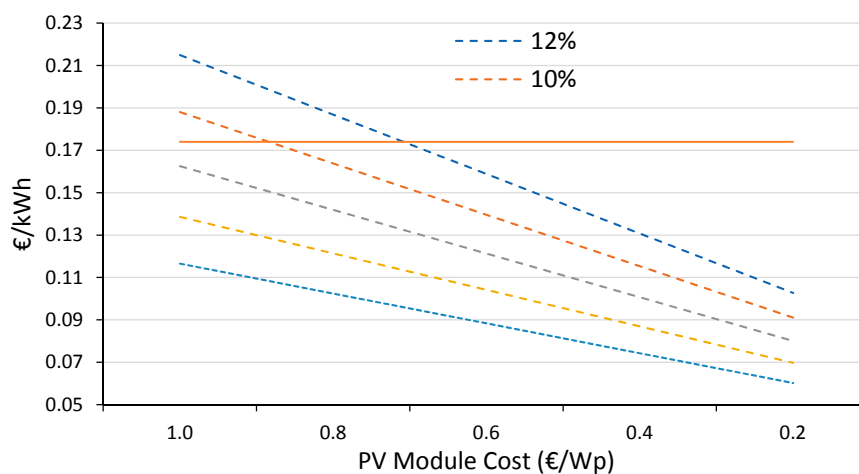


Figure 15. Analysis of the LCOE against the retail electricity cost at various interest rates (500,000 W inverter, deterministic method).

3.3.2. 500 kW Case Study Sensibility Analysis

For the 500 kW case study a sensibility analysis has been performed considering a range of annual yields from 1100 to 1500 kWh/kWp with a step of 100 kWh/kWp in the range. Using the methodology applied in Section 3.1.1, it is possible to calculate the LCOE considering the method described previously, fixing the regulated tariff at 17.4 c€/kWh including taxes and with a fixed interest rate of 10%.

Table 14 shows the most relevant results for the five cases. Case 1 corresponds to 1100 kWh/kWp and Case 5 corresponds to 1500 kWh/kWp. The positions where the LCOE is lower than the retail cost of energy have been highlighted.

Table 14. Comparison of the LCOE based on the different annual yield for 500 kW.

PV Module Cost (€/Wp)	System Cost (€)	Annual Yield (kWh/kWp):	LCOE (€/kWh)				
			Case 1 1100	Case 2 1200	Case 3 1300	Case 4 1400	Case 5 1500
1.0	1,022,450		0.188	0.174	0.162	0.151	0.143
0.8	877,250		0.164	0.152	0.141	0.132	0.125
0.6	732,050		0.140	0.129	0.121	0.113	0.107
0.4	586,850		0.115	0.107	0.100	0.094	0.089
0.2	441,650		0.118	0.110	0.103	0.097	0.091

Table 11 considers five cases, but the cost at 0.4 €/Wp is considered as the current scenario. For that reason, the PDF for the panel cost is log-normal with a mean of 0.4 (€/Wp) and a standard deviation of 0.2 (€/Wp). The panel cost floor is set at 0.2 (€/Wp) so that 95% of the cases are represented in the PDF (Figure 16).

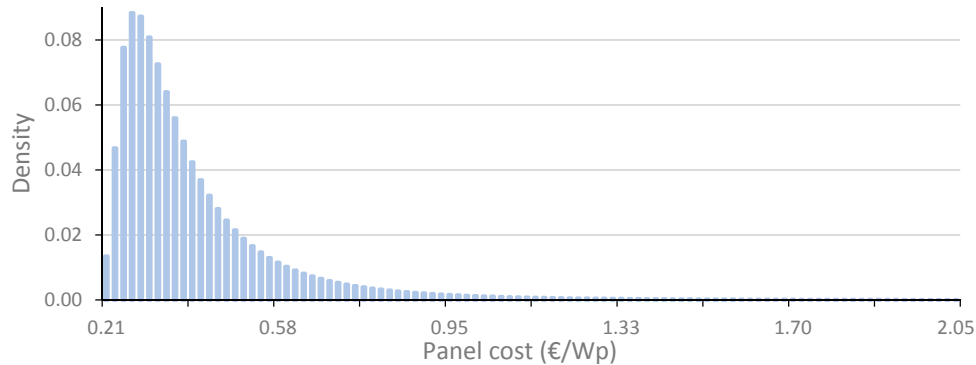


Figure 16. PDF of panel cost for a 500 kW system.

Introducing all the variables in the probabilistic analysis with the Monte Carlo method delivers a wide range of results, giving the following representation (Figure 17), with the frequency of the LCOE above and below the retail electricity cost.

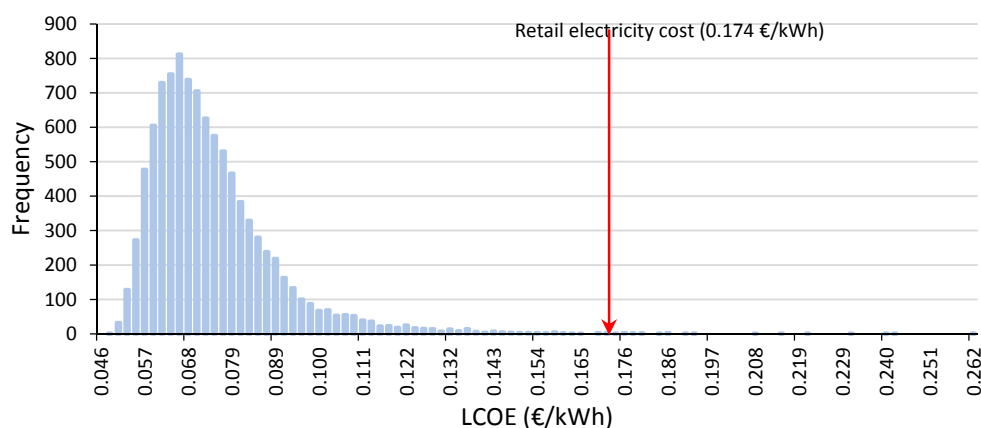


Figure 17. Histogram of the LCOE calculated with the Monte Carlo method for a 500 kW system.

Introducing the results of the iterations given by the Monte Carlo method for the business model, we obtain the IRR values. The IRR results for the 500 kW business case are shown graphically in Figure 18.

A success rate parameter (%) is introduced by counting the number of iteration results below the retail cost of the electricity and dividing by the total number of iterations (10,000). Analysing the frequency of the results and the value itself, the success rate for each case can be calculated. In this case of a 500 kW installation, it has been concluded that the success rate would be 99.80%. This means that in 99.80% of the cases, grid parity is achieved as the LCOE is lower than the retail cost. As a business case, the mean of the IRR is positive (14.34%). Therefore, it can be concluded that even though the loan input in the model contributes negatively, the investment is successful.

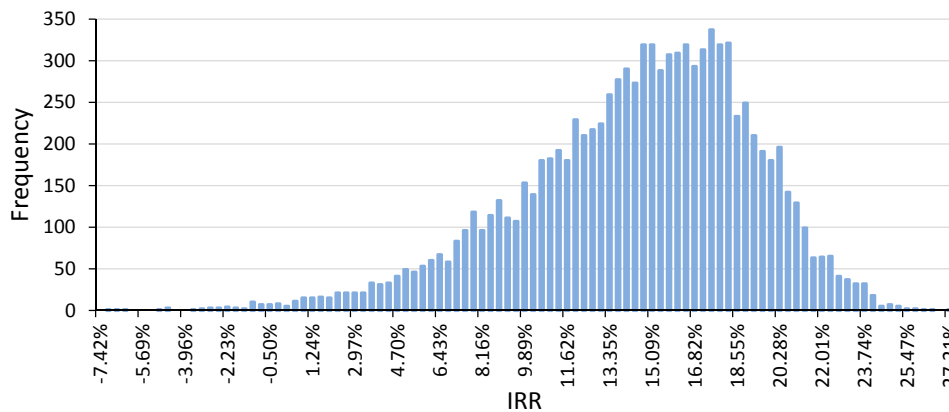


Figure 18. Histogram of the IRR calculated with the Monte Carlo method for a 500 kW system.

4. Discussion

In this paper, the effects of financial cost on PV grid parity are discussed. The study has been carried out using a probabilistic method (Monte Carlo), considering three cases corresponding to three PV installations of different sizes (5 kW, 50 kW and 500 kW of inverter power).

First, for each case, the deterministic calculation of the LCOE is performed; obtaining the most unfavourable case for all the variables that can be used to perform a sensitivity analysis. The aim of this calculation, considering pessimistic values, is to set the minimum value for the LCOE.

The first case corresponds to a PV installation of 5 kW (inverter power). The worst-case scenarios considering a 10% interest rate and a 1100 kWh/kWp yield have been calculated manually (Table 4). With these results, a bottom line can be drawn and considered a floor. In Table 6, a summary of the LCOE for each annual yield is represented. The positions where the LCOE is lower than the retail cost of energy have been highlighted, so we can say that in these conditions, grid parity is already reached. In the deterministic calculation method, it could be determined that the LCOE would reach the retail electricity cost at an interest rate of 4% (Table 5) for any module cost. Table 6 shows that a module cost 0.2 €/Wp in areas with 1200 kWh/kWp (and above) is necessary to achieve grid parity, and in areas with an annual yield of 1300 kWh/kWp (and above), grid parity could be reached with a module cost of 0.4 €/Wp. It can be concluded that for a small installation of 5 kW, grid parity will be achieved if the module cost is between 0.2 and 0.4 €/Wp at a fixed interest rate of 10% in areas from 1200 kWh/kWp and above.

The second case corresponds to a PV installation of 50 kW. This case is summarised in Tables 8–10. In the deterministic calculation method, it can be determined that the LCOE would reach the retail energy cost at the interest rate of 6% for any module cost, but this can also be determined at an interest rate of 10% (Table 9) and a cost between of 0.6 and 0.4 €/Wp and below. Table 10 shows that grid parity in areas with 1400 kWh/kWp (and above) is already achieved in any case. In areas with an annual yield of 1300 kWh/kWp and 1200 kWh/kWp, grid parity could be reached at any cost except with a module cost of 1 €/Wp and a fixed interest of 10%. In areas with an annual yield of 1100 kWh/kWp, grid parity is already achieved for a module cost of 0.6 €/Wp and below. Finally, it can be concluded that for the case of 0.8 €/Wp, grid parity is already achieved for an area with an annual yield of 1200 kWh/kWp and above (Table 10), which in the Spanish case means the majority of the territory.

The third case corresponds to a PV installation of 500 kW. This case is summarised in Tables 12–14. With the deterministic calculation method, it can be determined that the LCOE would reach the retail energy cost at an interest rate of 8% (Table 13) for any module cost, but this can also be determined at an interest rate of 10% and a cost of 0.8 €/Wp and below. Areas with an annual yield of 1200 kWh/kWp and above have already achieved grid parity in any case. In areas with an annual yield of 1100 kWh/kWp, grid parity could be reached at any cost except with a module cost of 1 €/Wp. For a module cost of 0.6 €/Wp and below, grid parity is achieved in any case, so it can be concluded that for the current scenario, grid parity is already achieved (Table 14).

The deterministic calculation methodology allows us to reach several conclusions. In small installations, grid parity will be reached depending on the financial model and the cost of the installation. In middle-scale installations, grid parity is already achieved, except for some geographical cases with an annual yield of 1100 kWh/kWp. Large-scale installations can be connected without any tariff, as the cost of energy is lower than the retail cost of energy at any case.

The probabilistic method (Monte Carlo) has been evaluated precisely for all the variable inputs if grid parity is achieved and how profitable the installation can be as a business. In Table 15, it can be determined when the LCOE is achieved, considering a recovery factor value of 0.1102. The representative cases where the LCOE is lower than the retail cost of energy have been highlighted.

Table 15. Comparison of the LCOE based on the Monte Carlo method for all the cases.

PV Module Cost (€/Wp)	LCOE (€/kWh)		
	5 kW	50 kW	500 kW
1	0.2756	0.2154	0.1585
0.8	0.2514	0.1911	0.1385
0.6	0.2271	0.1669	0.1184
0.4	0.2029	0.1427	0.0984
0.2	0.1787	0.1184	0.0783

Table 16 shows when the IRR is positive; this means the investment can be considered a business. The representative cases where the IRR is positive have been highlighted.

Table 16. Comparison of the IRR based on the Monte Carlo method for all the cases.

PV Module Cost (€/Wp)	IRR (%)		
	5 kW	50 kW	500 kW
1	−4.81	−2.05	−0.32
0.8	−3.83	−0.53	1.67
0.6	−2.68	1.39	4.36
0.4	−1.31	3.97	8.02
0.2	0.40	7.46	14.52

Finally, the means applied to the variables can be taken into consideration. These means defining the likelihoods defined across this paper where the panel cost is key to determine the LCOE and the IRR. Table 17 presents a summary that determines the results for the full range of options that we have determined for all the variables, which have been represented across this paper. The success rate represented in Table 17 determines the percentage of how many cases of LCOE have resulted above the retail electricity cost. As can be seen in Table 17, the rate is quite high. However, the financial parameters, such the interest rate, loan duration and amount loaned, significantly impact the IRR.

Table 17. Summary of the means of IRR and LCOE extracted from the Monte Carlo method for all the cases.

Power (kW)	Mean PV Module Cost (€/Wp)	Mean Yield (kWh/kWp)	Mean Interest Rate (%)	Mean LCOE (€/kWh)	Mean IRR (%)	Success Rate (%)
5	0.8	1300	6	0.1494	−0.97	82.26
50	0.6	1300	6	0.1019	5.92	99.59
500	0.4	1300	6	0.0727	14.34	99.80

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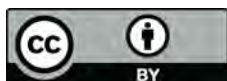
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