MONTE-CARLO PROBABILISTIC VALUATION OF CONCENTRATED SOLAR POWER SYSTEMS IN SPAIN UNDER THE 2014 RETROACTIVE REGULATORY FRAMEWORK

Please, cite this article as:

Sergio Coronas, Helena Martín, Jordi de la Hoz, Luis García de Vicuña, Miguel Castilla. MONTE-CARLO probabilistic valuation of concentrated solar power systems in Spain under the 2014 retroactive regulatory framework. Renewable and Sustainable Energy Reviews, Volume 138, 2021, 110670, ISSN 1364-0321

https://doi.org/10.1016/j.rser.2020.110670

MONTE-CARLO PROBABILISTIC VALUATION OF CONCENTRATED SOLAR POWER SYSTEMS IN SPAIN UNDER THE 2014 RETROACTIVE REGULATORY FRAMEWORK

Sergio Coronas[a,c]*, Helena Martín[a,c], Jordi de la Hoz[a,c], Luis García de Vicuña[b,d], Miguel Castilla[b,d]

[a] Department of Electrical Engineering

[b] Department of Electronic Engineering

[c] Escola d'Enginyeria de Barcelona Est (EEBE), Av. Eduard Maristany, 16, 08019 Barcelona,

Universitat Politècnica de Catalunya (UPC)

[d] Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSEVG),

Av. Víctor Balaguer, 1, 08800 Vilanova i la Geltrú, Universitat Politècnica de Catalunya (UPC)

*Corresponding author. Tel.: +34 934 137 325; fax: +34 934 137 401

E-mail address: sergio.coronas@upc.edu (Sergio Coronas)

Abstract

The current Royal Decree 413/2014 legal-economic framework for concentrating solar power plants in Spain has been analysed from a probabilistic perspective. Due to the high inherent risk in most of the parameters defining this economic regime, the use of a probabilistic model is proposed to perform the economic valuation of these facilities. A methodology composed of different steps has been developed and applied to a representative concentrating solar power plant type with thermal energy storage. This method has proven useful for distinguishing the input parameters to be considered as stochastic by using a sensitivity analysis, and also for performing the probabilistic valuation by using the discounted cash flow-Monte Carlo analysis. The results have revealed a great variability in the several output economic indicators considered. In general terms, substantial reductions in the profitability of these facilities have been evidenced with respect to the deterministic analysis under the current reality of the sector.

Keywords

CSP, Renewable energy, Retroactivity, Regulatory framework, Spain, Probabilistic valuation, Monte Carlo

Word count

8021 words (original version)

9422 words (revised version)

Nomenclature

Acronyms

CSP: Concentrating Solar Power

CSPP: Concentrating Solar Power Plants

DCF: Discounted Cash Flow

IQR: Interquartile Range

IRR: Internal Rate of Return

LCOE: Levelized Cost of Electricity

MC: Monte Carlo

MO: Ministerial Order

NPV: Net Present Value

PDF: Probability Density Function

RD: Royal Decree

RDL: Royal Decree-Law

RES: Renewable Energy Systems

SCSPP: Spanish Concentrating Solar Power Plants

SCSPS: Spanish Concentrating Solar Power Sector

SR: Specific Remuneration

TES: Thermal Energy Storage

WACC: Weighted Average Cost of Capital

Variables and parameters

a: year in which a CSPP obtained the operating permit

a_t: year in which a CSPP of type t obtained the operating permit

$C_{j,a}$: coefficient representing the investment cost of a CSPP obtaining the operating permit in the year a that cannot be recovered with the market revenue within *j*

$Capital_i$: capital of the facility in the year *i* [€]

$Cexp_i$: standard operating cost per unit of installed power for a year *i* under the RD 661/2007 [€/MW]

$Cexpf_i$: standard operating cost per unit of installed power within the year *i* under the RD 413/2014 [€/MW]

C_Eexpf_i: standard operating cost per unit of generated energy in the year *i* under the RD 413/2014 [€/MWh]

C_Eexpf_{2014}: standard operating cost per unit of generated energy of the CSPP in the year 2014 under the RD 413/2014 [€/MWh]

$C\_Eexp\_e_i$: standard operating cost per unit of generated energy in the year *i* under the RD 661/2007 [€/MWh]

d_i: weighting factor reducing $SR\_Revenue_i$ according to Nh_inst_i

$Debt\_opening\_cost$: percentage value of the debt opening cost [%]

$Depreciation_i$: depreciation of the facility in the year *i* [€]

E_i: total energy generated within the year *i* [MWh]

$EBIT_i$: Earnings Before Interest and Taxes of the facility in the year *i* [€]

$Equity$: value of the equity [%]

$ETax\_Cost_i$: tax on the produced energy in the year *i* [€]

E_max_i: maximum value of E_i eligible for perceiving the Ro_i [MWh]

FIT_i: feed-in tariff in the year *i* for a CSPP under the RD 661/2007 [€/MWh]

F_OMC_i: fixed operating cost in the year *i* per unit of installed power [€/kW]

F_OMC_{a+1}: fixed operating cost within the year $a+1$ [€/kW]

$Fixed\_OMC_i$: fixed operating cost in the year *i* [€]

Ing_i: standard income per unit of installed power for a year i under the RD 661/2007 [€/MW]

$Ingf_i$: standard operating income per unit of installed power within the year i under the RD 413/2014 [€/MW]

Int_Rate: value of the loan fixed interest rate [%]

$Interest_i$: interest of the facility in the year i [€]

INV_Cost: investment cost [€/W]

Inv_R_i: remuneration for the investment in the year i [€]

IPC_i: Consumer Price Index for the year i [%]

ir: year in which the investment is recovered

j: three-year half-period

k_d: financial cost of the debt [%]

K_j: capital recovery factor

K_R: physical yearly degradation rate [%]

K_{RR}: standard yearly degradation rate under the RD 413/2014 [%]

lp: last period with negative accumulated *Project_CashFlow* [years]

LR: reasonable profitability [%]

$LI1_{i,j}$, $LI2_{i,j}$: lower limits for the calculation of $Vajdm_{i,j}$ [€/MWh]

$LS1_{i,j}$, $LS2_{i,j}$: upper limits for the calculation of $Vajdm_{i,j}$ [€/MWh]

$Market\_Revenue_i$: market revenue perceived in the year i [€]

nd: number of years for the depreciation of the asset [years]

$Nh_{i,j}$: standard equivalent operating hours within the year i of j under the RD 413/2014 [h]

Nh_{2014}: standard equivalent operating hours of the CSPP within the year 2014 under the RD 413/2014 [h]

Nh_e_i: standard equivalent operating hours within the year i under the RD 661/2007 [h]

Nh_inst_i: actual equivalent operating hours within the year i under any regulatory framework [h]

Nh_inst_{a+1}: initial value of Nh_inst_i [h]

$Nh\_max_{(Ro)i}$: maximum value of Nh_inst_i eligible for perceiving the Ro_i [h]

Nh_min_i: minimum value of Nh_inst_i that does not entail a reduction of $SR\_Revenue_i$ [h]

$nyrd$: number of years to replace the debt or term of the loan [years]

Op_R_i: remuneration for the operation in the year *i* [€]

$Operating\_Cost_i$: total operating cost for running the facility [€]

p: first complete year of j

P_n: rated power [MW]

Pm_i: average energy market price per unit of generated energy in the year *i* [€/MWh]

Pmf_i: future estimated average market price per unit of generated energy for the year *i* [€/MWh]

Pm_e_i: revenue per unit of generated energy in the year *i* under the RD 661/2007 [€/MWh]

$Project\_CashFlow_i$: cashflow of the CSPP in the year *i* [€]

$Project\_IRR$: internal rate of return of the CSP project at the end of *VU* [%]

$Project\_LCOE$: levelized cost of electricity of the CSP project at the end of *VU* [€/MWh]

$Project\_NPV$: net present value of the CSP project at the end of *VU* [€]

$Project\_Payback$: payback of the CSP project at the end of *VU* [years]

PT_IRR_i: pre-tax internal rate of return up to the year i [%]

r_i: curtailment for IPC_i [%]

$Real\_Taxes_i$: taxes of the facility in the year i [€]

REH: Reference Equivalent Hours (RDL 14/2010) [h]

$Revenue_i$: total revenue perceived in the year i [€]

$Rinv_{j,a}$: remuneration for the investment per unit of installed power in a year i within j of a CSPP obtaining the operating permit in the year a [€/MW]

Ro_i: remuneration for the operation per unit of generated energy in the year i [€/MWh]

$RTax\_Cost_i$: tax on the remuneration of the produced energy in the year i [€]

sm: number of years of j

SB_j: average yield during determined period of the 10-year Spanish bonds in the secondary market within j [%]

$SR\_Revenue_i$: SR revenue perceived in the year i [€]

$Stakeholders\_payment$: percentage value of the stakeholders' payment [%]

t: type facility code

t_j: per unit discount rate within j corresponding to the reasonable profitability

Tax_Rate: rate of corporate tax [%]

Tax_E: tax on the produced energy [€/MWh]

Tax_R: tax on the remuneration of the produced energy [%]

Uf_i: threshold of Nh_inst_i for perceiving $SR\_Revenue_i$ [h]

$Vajdm_{i,j}$: coefficient adjusting the deviations of Pm_i from Pmf_i

VI_a: standard value of the initial CSPP investment per unit of installed power [€/MW]

$VNA_{j,a}$: net value per unit of installed power in a year *i* within j of a CSPP obtaining the operating permit in the year a [€/MW]

VR_j: remaining number of years at the beginning of j to the end of the facility VU [years]

VU: regulatory lifetime [years]

V_OMC_i: variable operating and maintaining cost in the year *i* per unit of generated energy [€/MWh]

V_OMC_{a+1}: variable operating and maintaining cost within the year $a+1$ [€/MWh]

$Variable\_OMC_i$: variable operating and maintaining cost in the year *i* [€]

$WACC$: Weighted Average Cost of Capital (discount rate for the profitability analysis) [%]

ΔIPC_i: difference between the IPC_i and the inflation rate at constant tax excluding unprocessed food and energy products [%]

Δk_d: differential added to the financial cost of the debt for determining the opportunity cost ratio of shareholders [%]

Δt_j: differential added to SB_j for determining t_j [%]

Δ_Std_Cost: yearly increase in standard operating cost per unit of generated energy under the RD 413/2014 [%]

1. Introduction

Cumulative global Concentrating Solar thermal Power (CSP) capacity reached 5.5 GW in 2018, experiencing a growth of 11% over the previous year. It was the most important annual increase since 2014, evincing the vitality of the sector. Spain remained the global leader in cumulative CSP capacity with 2,304 MW at the end of 2018 (42.20% of the world total), followed by the United States, with over 1,738 MW. However, for the third consecutive year, new capacity came online only in emerging markets such as China and Morocco, which led the CSP capacity gain, followed by South Africa and Saudi Arabia [1].

Just as the CSP market dynamism, and as denoted in the previous work of the authors [2], the research on CSP has gained much importance in the last decade. The analysis of the scientific literature indicates the predominance of the technical studies among those focused on a purely economic thematic area [3-23] or those that combine technical and economic considerations [24-42]. Thus, the articles related somehow to the economic field, including those devoted to the economic valuation of concentrating solar power plants (CSPP), represent only a tiny part of the whole CSP state of the art.

The set of articles addressed to the economic appraisal of CSPP could be classified into two groups. In the first group there would be those articles that are based on deterministic analysis to carry out their economic assessment [3-4,7-14,16-17,24-30,32-35,37-39,41-42]. In most of these papers the deterministic analysis was based on the calculation of a single economic indicator. In this sense, the most used was the levelized cost of electricity (LCOE), followed by the net present value (NPV), the payback and the internal rate of return (IRR). Although to a lesser extent, it is also worth mentioning the use of other economic indicators such as the benefit-cost ratio, the profitability index and the return on investment. In addition, China was the country that attracted further attention [10-12,32-33], followed by Australia [9,26,30], United States [28-30], India [13-14], North Africa [16,35], Chile [17,38] and Spain [24,37], among others.

In the same group, there would be as well those articles based on the what-if scenarios method as an approximation to the stochastic analysis. This kind of articles is located halfway between the deterministic and the probabilistic approach. The what-if scenarios analysis helps to assess the effects of discrete inherent risk by defining different potential future scenarios for a limited number of input parameters identified as uncertain. Usually, these scenarios represent the most likely case (base scenario), and extreme cases, i.e., the best-case scenario and the worst-case scenario [43-45]. In most of the papers of the first group, scenarios were used in their economic valuations. Among the main input parameters used in these what-if scenarios were the discount rate, the direct normal irradiance, the capital cost and the operating costs.

In the second group there would be those articles that treat the non-deterministic economic valuation of CSP assets using the discounted cash flow (DCF)-Monte Carlo (MC) method [18,20-23,31,36]. In all of these articles except [18], the MC analysis relied on the calculation of the LCOE. Likewise, the main stochastic input parameters were the fixed and variable operating costs, the capital and investment cost, the discount and inflation rates, the capacity factor and the asset lifetime. Moreover, from the location analysis point of view, the United States was the country that deserved more considerable attention among all these articles [20,22-23], followed by Chile [18], Australia [31] and Italy [36].

Some insights can be drawn through the state of the art analysis. First of all, it should be highlighted the limited number of studies analysing the regulatory framework applied to the CSPP and its economic implications [2,46-49]. This fact is at least surprising when considering the significant impact that regulatory frameworks have on the economic performance of renewable energy assets [2,50-52]. On this subject, the lack of attention to the regulatory framework when determining the economic valuation of CSPP might be pointed out as a relevant gap in the scientific literature.

In this regard, and as far as the authors know, only the deterministic approaches in [2] and [49] have considered the regulatory framework in the economic valuation of a CSPP in Spain. This lack of studies is not aligned with the global CSP capacity leadership of Spain, with assets exceeding 13,000 M€ [2]. It also ignores the deep impact introduced by the drastic reform of the Spanish regulatory framework for renewable energy systems (RES), i.e., the Royal Decree (RD) 413/2014, as a result of which no new CSP capacity has entered commercial operation in Spain since 2013.

Moreover, no studies have used a non-deterministic approach to undertake the economic valuation of the CSPP in Spain. This avoidance is relevant due to the inherent variability in many parameters affecting the assessment, and even more so if the complex legal and economic framework RD 413/2014 applied to the Spanish CSP sector (SCSPS) has to be taken into account [2].

Accordingly, this work is aimed to fill the three gaps mentioned above as it is the first one jointly combining the necessary analysis of the economic and regulatory framework by using a non-deterministic method in the valuation of Spanish CSP assets.

To this end, the reason for the necessary probabilistic economic analysis of CSP assets under the RD 413/2014 framework is firstly described and justified. A description of the complexity and particularities of this economic framework is carried out identifying all the input parameters and intermediate calculation variables that define the economic model. In the same way, a brief comparison between the deterministic and the probabilistic approach is performed (Section 2). Then, it is proceeded with the description of the methodology for carrying out the stochastic economic valuation of CSP assets under the RD 413/2014 (Section 3). Thereupon, a case study representative of the SCSPS is defined and justified (Section 4).

Next, it goes on to simulate the economic model and obtain results. To that end, a sensitivity analysis is firstly carried out for the selection of the input parameters to be considered as stochastic. Then, the characterization of the stochastic parameters is conducted, to subsequently perform the DCF-MC simulation of the case study and show a summary with the obtained results (Section 5). Afterward, these economic results are analysed and compared with those obtained in the deterministic case (Section 6). In closing, all the factors deemed relevant for the SCSPS are duly systematized and conclusions are raised (Section 7).

2. Problem statement

The enormous complexity that the RD 413/2014 economic and regulatory framework has introduced in the Spanish concentrating solar power plants (SCSPP) remuneration mechanism significantly hampers their economic valuation. As evidenced in [2,50], the current remuneration scheme retroactively applied from 2013 on, requires a large number of input parameters as well as intermediate calculation variables, some of which of high complexity. Most of these parameters are of economic and financial nature with regulatory assigned values.

Furthermore, as specified in the Law 24/2013 of the Spanish electricity sector [53], the remuneration parameters will be set for six-year regulatory periods, taking into account the cyclical situation of the economy, the electricity demand and the reasonable profitability for the activities of energy production from RES. Thus, with the exception of the standard value of the initial investment per unit of installed power (VI_a) and the regulatory lifetime of the installation type (VU), all regulatory parameters can be reviewed and updated at the end of each six-year regulatory period by the Spanish Government. Among them, the standard estimated future market price per unit of generated energy (Pmf_i), as well as the remuneration parameters directly related to this one, can even be reviewed at the end of every three-year regulatory half-period j.

In order to perform the economic valuation of the income statement of the CSP facilities under the RD 413/2014 framework, apart from the $Revenue_i$'s calculation, which is the output variable of the remuneration scheme, additional economic-financial computations are required. In Fig. 1, the complete model for the economic assessment of the CSP facilities has been globally represented by means of a conceptual block diagram. For completeness, this model is also prepared to take into account the remuneration obtained by the CSP assets under the former regulatory frameworks in force prior to the RD 413/2014.

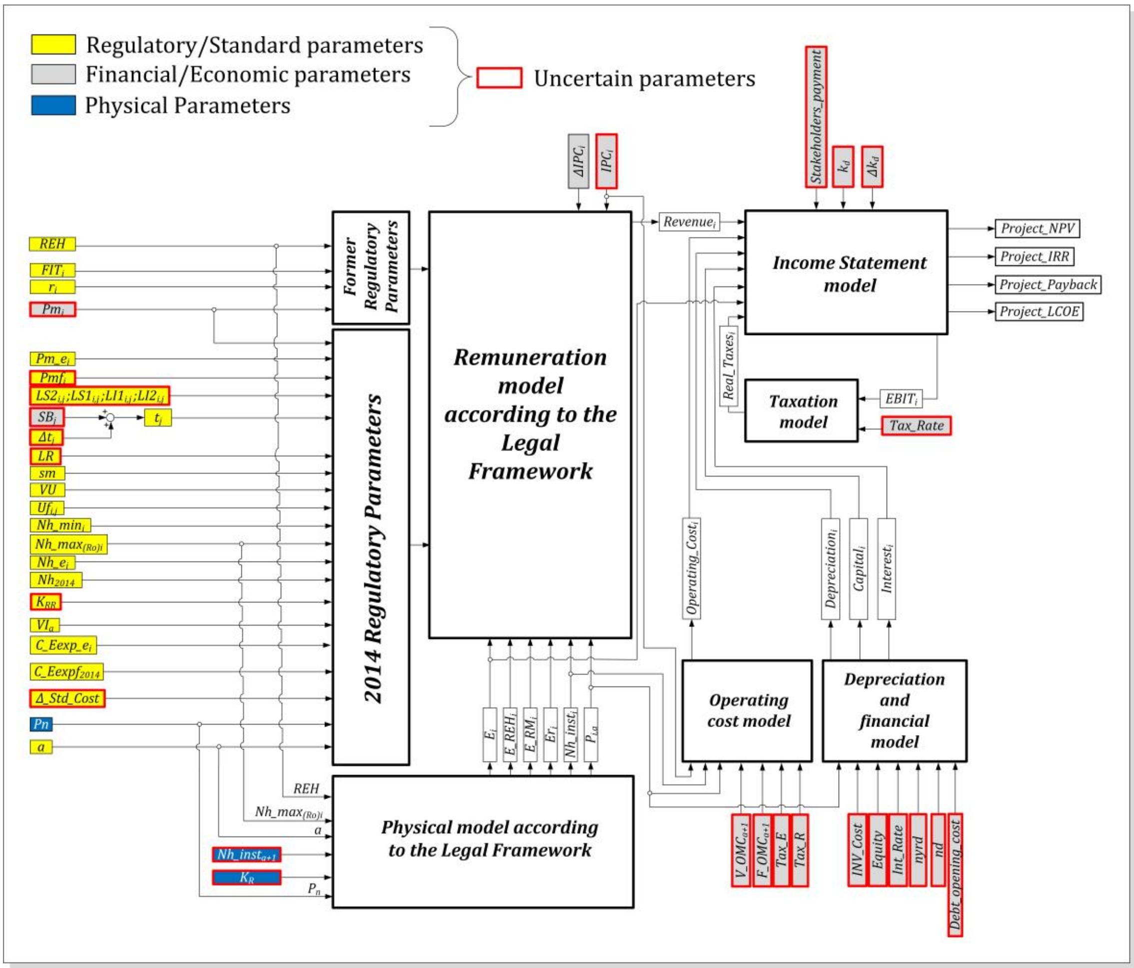


Fig. 1. Conceptual scheme of the income statement model for the economic valuation of Spanish CSP assets under the RD 413/2014 framework. Source: self-elaboration based on [2].

As observed in Fig. 1, the input parameters are classified according to their typology in different coloured boxes. The economic and financial parameters with regulatory assigned values are put into yellow-coloured boxes, those of economic and financial type with values not regulatory set are placed into grey-coloured boxes, while those of physical nature are put into blue-coloured boxes. In addition, those parameters presenting a greater uncertainty and unknown evolution over time are framed in red colour. The present probabilistic economic analysis is carried out focusing on these twenty-eight uncertain input parameters.

The general economic calculation scheme is divided into six sub-models represented in six different blocks, as seen in Fig. 1. The main sub-model is the “Remuneration model according to the Legal Framework”, which produces the annual income of the CSP facility ($Revenue_i$). This remuneration scheme receives as inputs, on one hand, the regulatory remuneration parameters of both the current RD 413/2014 regulatory framework “2014 Regulatory Parameters” and the previous frameworks “Former Regulatory Parameters”. And, on the other hand, it also needs some physical variables calculated in the “Physical model according to the Legal Framework” block, among which the annual energy generated by the CSPP (E_i) and the annual number of operating hours (Nh_inst_i) stand out. The mathematical formulation defining this remuneration scheme is displayed in Appendix A. However, for a detailed explanation of each of the equations related to the RD 413/2014 remuneration model the interested reader is addressed to [2].

Once the $Revenue_i$ is obtained, the annual operating costs ($Operating\_Cost_i$) are calculated through the “Operating cost model” block. This block receives as inputs the fixed (F_OMC_{a+1}) and variable costs (V_OMC_{a+1}) of the CSP facility within the year $a+1$, as well as the electricity taxes, i.e., the tax on the produced energy (Tax_E) and the tax on the remuneration of the produced energy (Tax_R) (see Appendix A for full details of the equations defining the operating cost scheme). Next, the depreciation ($Depreciation_i$), the capital ($Capital_i$) and the interests ($Interest_i$) in the year i are computed by the “Depreciation and financial model” block, receiving as input parameters the investment cost (INV_Cost), the equity ($Equity$), the loan fixed interest rate (Int_Rate), the number of years to replace the debt ($nyrd$), the number of years for the depreciation of the asset (nd) and the debt opening cost ($Debt\_opening\_cost$). Likewise, the “Taxation model” block renders the $Real\_Taxes_i$, on the basis of the rate of corporate tax (Tax_Rate) and the earning before interests and taxes in the year i ($EBIT_i$). Finally, the output variables of these five sub-models, as well as parameters such as the financial cost of the debt (k_d) and the differential added to the financial cost of the debt (Δk_d), necessary for the calculation of the weighted average cost of capital ($WACC$), come together as inputs into the "Income Statement model". This last block is responsible for assessing the impact of the legal framework in the economic results of the CSP assets. Note that the RD 413/2014 economic model uses a DCF scheme, that is, all the year-by-year cash flows calculated for the entire useful life of the CSP facility are updated to present values using a discount rate, which in this work is the *WACC*.

This economic valuation is based on the analysis of four widely used economic indicators, such as the project net present value (*Project_NPV*), the project internal rate of return (*Project_IRR*), the project payback period (*Project_Payback*) and the project levelized cost of electricity (*Project_LCOE*). The *Project_NPV* indicates the difference between the monetary value and the cost of the CSP project throughout its useful life. As for the *Project_IRR*, it states the profitability of the CSP project at which the *Project_NPV* is zero. Likewise, it clearly denotes the limit profitability that this project can generate. The *Project_Payback* shows the time required to recover the initial investment made. Regarding the *Project_LCOE*, it reflects the price per unit of energy at which to sell the electricity produced to obtain a *Project_NPV* equal to zero at the end of the project useful life. For a detailed definition of the formulation of these economic indicators, see Appendix A. For reasons of brevity, however, the equations defining some of the above described variables has been here omitted for being widely well-known and easily drawn from the financial literature.

Therefore, given the high uncertainty associated to the future evolution of many of the current economic regime parameters, and its effect on the income statement results of Spanish CSP facilities, there is a need to carry out a stochastic economic valuation taking into account the high inherent risk. Thus, providing a new insight that improves the deterministic approach deemed on the previous article of the authors [2].

The deterministic approach, which is the simplest method, shows a fixed output picture of a specific situation defined by constant input parameters throughout the analysis period. This method is very limited in terms of quantifying and assessing the possible impact of the risk existing in the analysed system. Any deviation with respect to the fixed scenario defined in the deterministic scheme can lead to significant variations in the output results not properly foreseen, which can greatly hinder the decision-making process in the management of the system. By contrast, the probabilistic method incorporates a broader range of possible output results to know what can happen in the system under different plausible scenarios associated with its inherent risk. In this sense, this method is more complex and requires the execution of a much broader sequence of steps than the deterministic scheme. Furthermore, in the stochastic method, the probability density function (PDF) characterising each of the uncertain parameters must be defined as precisely as possible so that the subsequent analysis is valid and reliable in terms of decision-making [43].

Focusing on the Spanish CSP system under the RD 413/2014 framework discussed in this article, Fig. 2 depicts a visual comparison of the implications of carrying out a deterministic or a stochastic analysis. As stated above, a total of twenty-eight input parameters with a considerable degree of uncertainty have been identified in the Spanish CSP system under the current legal-economic framework.

In this regard, as can be seen in Fig. 2, carrying out a deterministic analysis in this CSP system would imply considering the set of uncertain input parameters $X=\{K_R$, Nh_inst_{a+1}, LR, Δt_j, Δ_Std_Cost, K_{RR}, Pmf_i, $LS2_{i,j}$, $LS1_{i,j}$, $LI1_{i,j}$, $LI2_{i,j}$, SB_j, IPC_i, Pm_i, V_OMC_{a+1}, F_OMC_{a+1}, Tax_E, Tax_R, $Equity$, Int_Rate, $nyrd$, $Debt\_opening\_cost$, $Stakeholders\_payment$, k_d, Δk_d, INV_Cost, nd, $Tax\_Rate\}$ constant throughout the analysis period. Consequently, this will always invariably produce the same set of output results *Y* for the *Project_NPV*, *Project_IRR*, *Project_Payback* and *Project_LCOE*. In the limit, a parameter with a fixed deterministic value can be interpreted as a parameter with a uniform PDF with a range of values starting and ending at the same value and with unit probability ($P=1$). Note that in the deterministic simulation, the values of the uncertain input parameters are the standard values defined by the Spanish Government for the chosen CSP case study.

On the other hand, the probabilistic analysis provides a way to examine the consequences of continuous risk, giving a more complete view of the risk impact on the model set of outcomes *Y*. Thus, while the deterministic method does not contemplate the existence of chance or uncertainty, the probabilistic method considers the degree of uncertainty of each stochastic input parameter by the use of a PDF. In the case of study, uniform and triangular PDF are considered. The stochastic model, which obtains the output results *Y* in a probability distribution form, is composed of a statistical sub-model to deal with the stochastic parameters defined by their PDF, apart from the deterministic model that is simulated in a loop structure until reaching the desired number of samples.

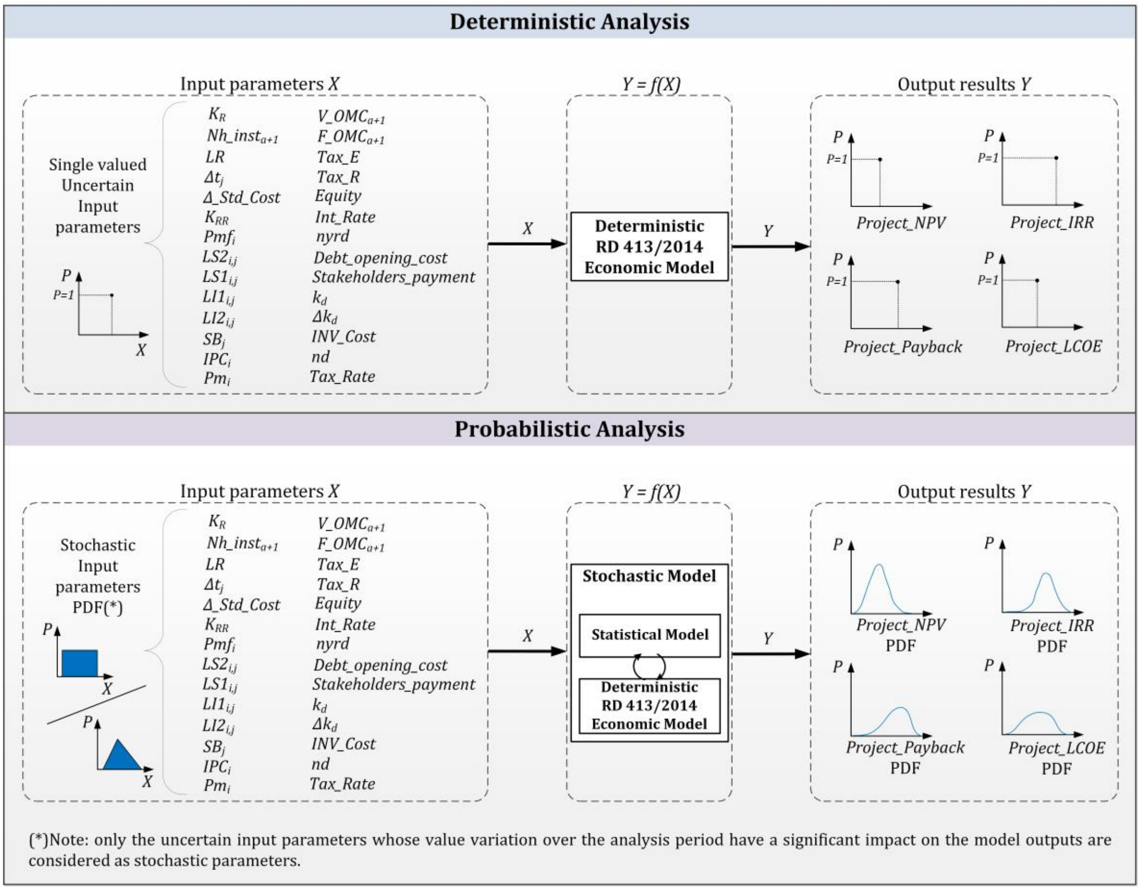
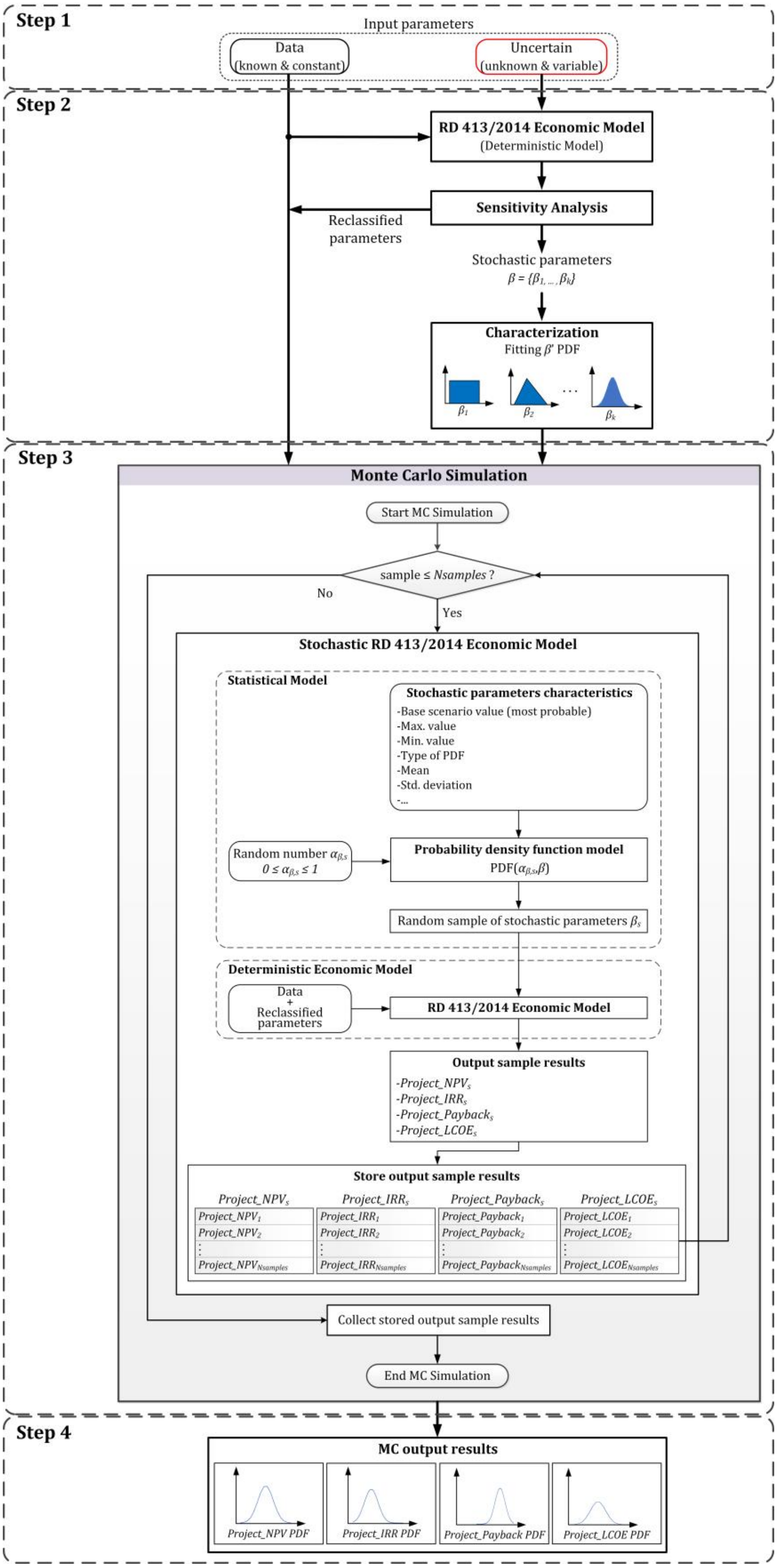


Fig. 2. Conceptual comparison schema between the deterministic and the probabilistic analysis of the Spanish CSP system under the RD 413/2014 framework. Source: self-elaboration.

3. Methodology

The present probabilistic economic assessment is carried out by using the DCF-MC approach. This method is one of the most active asset valuation approaches in practice, due to its relative simplicity compared to other methods (e.g. Real Options). In this regard, Fig. 3 provides a flow chart with the application methodology of the DCF-MC analysis to carry out the stochastic economic valuation of SCSPP under the RD 413/2014 economic and regulatory framework.



Step 1
Input parameters
Data (known & constant)
Uncertain (unknown & variable)
Step 2
RD 413/2014 Economic Model (Deterministic Model)
Sensitivity Analysis
Reclassified parameters
Stochastic parameters
Characterization
Fitting β' PDF
Step 3
Monte Carlo Simulation
Start MC Simulation
sample ≤ Nsamples ?
No
Yes
Stochastic RD 413/2014 Economic Model
Statistical Model
Stochastic parameters characteristics
-Base scenario value (most probable)
-Max. value
-Min. value
-Type of PDF
-Mean
-Std. deviation
Probability density function model
Random sample of stochastic parameters
Deterministic Economic Model
Data + Reclassified parameters
RD 413/2014 Economic Model
Output sample results
Store output sample results
Collect stored output sample results
End MC Simulation
Step 4
MC output results
Project_NPV PDF
Project_IRR PDF
Project_Payback PDF
Project_LCOE PDF

Fig. 3. Methodology for the application of the DCF-MC analysis in the RD 413/2014 economic model. Source: self-elaboration.

As observed in Fig. 3, the applied methodology consists of a sequence of four main steps. In the first step, all the input parameters required by the RD 413/2014 economic model (see Fig. 1) are initially classified into two groups. The first group is named “Data” and includes those parameters whose value is known and constant throughout the analysis time. The second group is called “Uncertain” and initially contains those parameters in which a greater uncertainty and variability is observed in the evolution of its value throughout the useful life of the CSP asset. A total of twenty-eight parameters are included in this second group (see the input parameters highlighted in red colour in Fig. 1), either due to economic, financial and regulatory uncertainty or because of the reluctance of the SCSPS to provide certain data.

All the input parameters sorted in the second group present an inherent risk associated with the existing uncertainty regarding the future evolution of their values. However, it cannot be assumed that these parameters will generate a significant impact on the output results of the economic model under study. Thus, as observed in Fig. 3, the second step has precisely as its main focus to discern which of the twenty-eight uncertain input parameters initially classified in the second group really represent a meaningful impact on the output of the RD 413/2014 economic model. To do so, the sensitivity analysis mathematical technique is applied to these uncertain parameters using the deterministic model. Whereas the input parameters of the first group are directly introduced into the MC simulation model without the need for prior processing.

In this way, the uncertain input parameters whose value variation does not represent a significant change in the output economic metrics are discarded and then, reclassified in the DCF-MC analysis as constant parameters of the first group. Note that the simulation values of these reclassified parameters of the second group, as well as of those of the first group, are the ones defined in the base scenario (see Tables 1-2). Hence, the DCF-MC analysis is focused on the "Uncertain" parameters whose value variation over the analysis period has a considerable effect on the model outcomes, the henceforth so-called stochastic parameters (*β*). At that point, the characterization of these stochastic parameters is conducted through their PDFs, which define their range of possible values and their probability to arise.

Then, in the third step, the DCF-MC simulation of the RD 413/2014 economic model is performed for a total number of samples (*Nsamples*). The DCF-MC model is basically formed by a statistical sub-model and the deterministic RD 413/2014 economic model shown in Fig. 1. As seen in Fig. 3, the statistical sub-model is responsible for calculating random scenarios for each of the existing stochastic parameters *β* in each sample(*s*). Thus, from the characteristics that define each of these stochastic parameters and a randomly generated number between zero and one for each stochastic parameter and each sample ($\alpha_{\beta,s}$), the PDF model obtains a random sample of each of these parameters (β_s). It is important to emphasize that, as mentioned in the previous section, the remuneration input parameters with regulatory assigned values can be reviewed either every three years or every six years. Similarly, other parameters of an economic nature, such as the average energy market price (Pm_i), are updated annually. Thus, in the specific case of these type of stochastic parameters, more than one variation per MC sample *s* over the CSPP lifetime is performed. Subsequently, the random samples obtained for each stochastic parameter β_s together with the known data (parameters of the first group and reclassified parameters of the second group) are entered into the deterministic RD 413/2014 economic model. As a result, the outcomes of the four analysed economic indicators for a sample *s* are rendered ($Project\_NPV_s$, $Project\_IRR_s$, $Project\_Payback_s$ and $Project\_LCOE_s$). These output sample results are stored and this process is repeated iteratively until *Nsamples* is reached.

Finally, in the fourth step depicted in Fig. 3, once the DCF-MC iterative process has finished, the results obtained for the four economic indicators are collected, determining the probability distribution and frequency of occurrence of these output variables under the associated uncertainties. Additionally, statistics of great relevance are calculated, such as the mean, the median, the variance, the standard error, the kurtosis, the asymmetry coefficient, the confidence interval, and maximum and minimum values, among others.

4. Case study definition

In order to cover the highest percentage of the Spanish CSP assets in the present stochastic economic valuation study under the RD 413/2014 framework, but providing a significant added value to this probabilistic analysis, it has been decided to select the most representative CSPP type with thermal energy storage (TES). Furthermore, it is important to highlight that since the approval of the retroactive and complex RD 413/2014 legal-economic framework in 2014, no new CSP capacity has been installed in Spain. Therefore, the analysis carried out in this work is based on a case study focused on the existing Spanish CSPP.

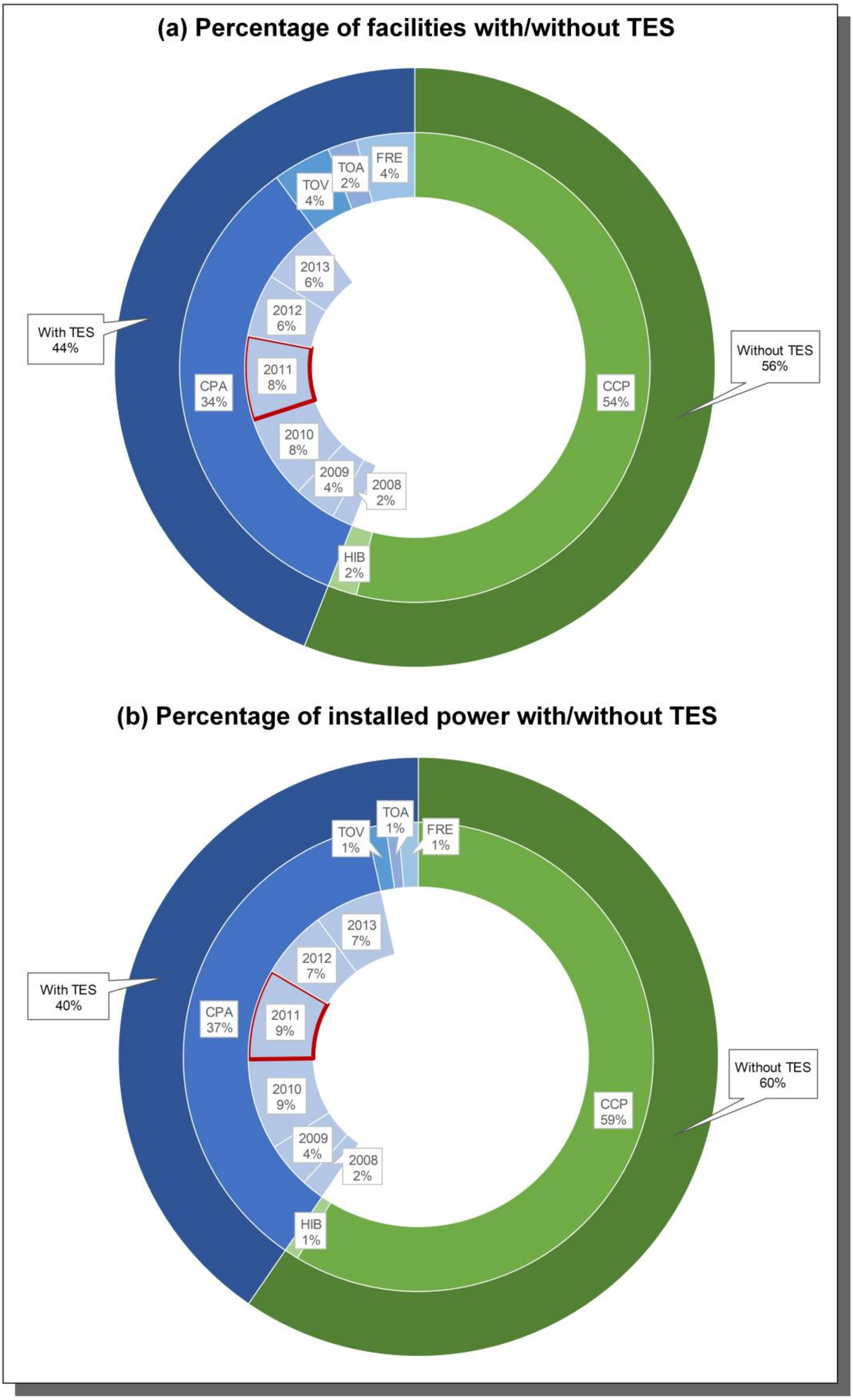

(a) Percentage of facilities with/without TES
With TES 44%
Without TES 56%
CPA 34%
CCP 54%
TOV 4%
TOA 2%
FRE 4%
HIB 2%
2013 6%
2012 6%
2011 8%
2010 8%
2009 4%
2008 2%
(b) Percentage of installed power with/without TES
With TES 40%
Without TES 60%
CPA 37%
CCP 59%
TOV 1%
TOA 1%
FRE 1%
HIB 1%
2013 7%
2012 7%
2011 9%
2010 9%
2009 4%
2008 2%

Fig. 4. Characterization of the SCSPS: (a) classification according to the total number of facilities, (b) classification according to the total installed capacity. Source: self-elaboration.

In the SCSPS there are a total of fifty CSP facilities accounting for 2,304 MW of installed capacity. Fig. 4 depicts the characterization of the SCSPS through the use of multilevel circular charts. Specifically, three different levels are used. In the external level, the Spanish CSP assets are classified according to whether they have a thermal storage system (blue-coloured area) or not (green-coloured area). In the intermediate level, CSP facilities are sorted according to their technology: parabolic trough without TES (CCP), parabolic trough with TES (CPA), saturated steam tower (TOV), molten salt tower (TOA), Fresnel (FRE) and hybrid type II (HIB). Finally, in the internal level, CSPP are classified according to the year in which they obtained the operating permit. This characterization is carried out both considering the total number of existing CSP facilities (Fig. 4a) and the total installed capacity (Fig. 4b).

Firstly, it can be observed that the SCSPS is divided into two almost equal parts between CSPP with and without TES. Specifically, 44% of the total number of CSPP in Spain correspond to facilities with TES, accounting for 40% of the total installed capacity; while the number of CSP facilities without TES represents 56% of the total, accounting for 60% of the global installed capacity (see external level of multilevel circular charts in Fig. 4). Secondly, it can be drawn the dominance of the parabolic trough technology in the SCSPS, representing 88% of the total number of CSPP in Spain and accounting for more than 95% of the total installed capacity. Going further, 34% of the total number of CSP facilities are of parabolic trough technology with TES, accounting for 37% of the total installed capacity in Spain; while CSP assets of parabolic trough technology without TES represent 54% of the total facilities and 59% of the global installed capacity (see intermediate level of multilevel circular charts in Fig. 4).

For this reason, it has been chosen as a case study a 50 MW CSP asset of parabolic trough technology with a TES capacity greater than 5h and less than or equal to 8h, which obtained the operating permit in 2011. The Ministerial Order (MO) IET/1045/2014 sorted the existing CSP plants into twenty different groups identified by consecutive type facility codes (*t*), ranging from IT-00601 to IT-00620, according to their technology subtype and the year in which they obtained the operating permit (a_t). In accordance with this classification, this CSP plant belongs to the type facility IT-00609. This type of CSP facility is the most numerous group among the CSP assets of parabolic trough technology with TES, representing 8% of the total number of CSPP in Spain and almost 9% of the total installed capacity (see internal level of multilevel circular charts in Fig. 4). Moreover, it is important to emphasise that parabolic trough, which represents around 70% of new capacity additions in 2018, and tower technologies continued to dominate the global CSP market [1].

Thus, although CSP assets with TES do not dominate the SCSPS, with the exception of integrated solar combined-cycle facilities, all CSP plants that entered operation in the world between the end of 2014 and the end of 2018 incorporated a TES system. In this sense, 16.6 GWh of TES was operational in conjunction with CSPP by the end of 2018, with an increase of almost 30% over the previous year [1].

Once the most representative type facility IT-00609 was selected and justified, the values of its regulatory parameters were extracted from the MO IET/1045/2014 [54] and the MO ETU/130/2017 [55] and listed in Table 1. Accordingly, the case study here analysed is based on the values established by the Spanish Government for a hypothetical “efficient and well-managed” CSP plant.

Table 1. Values of the regulatory parameters for a CSP type facility IT-00609. Source: self-elaboration based on [54-56].

Note: Table 1 has been inserted on a separate page at the end of this document due to its large size so that the structure of the entire document is not modified.

5. Model simulation and results

5.1. Sensitivity analysis

As stated in Section 3, the sensitivity analysis is aimed at distinguishing how many of the twenty-eight uncertain input parameters initially classified in the second group transmit substantially their risk to the output variables of the RD 413/2014 economic model. Only these parameters are considered as stochastic ones in the DCF-MC simulation. Conversely, the rest of the input parameters initially considered as uncertain are reclassified as constant parameters of the first group.

Prior to the execution of the sensitivity analysis simulation, the reference results for the *Project_NPV*, *Project_IRR*, *Project_Payback* and *Project_LCOE* are deterministically computed for a base scenario, defined in Tables 1-2, in accordance to the economic and regulatory reality of the SCSPS for a hypothetical "efficient and well-managed" CSP plant.

Table 2. Base scenario values for the "Uncertain" parameters considered in the sensitivity analysis of a CSP type facility IT-00609. Source: self-elaboration.

Parameters	Reference values	Source
Physical parameters		
- Physical degradation rate (K_R)	0.2%	[54]
- Initial equivalent operating hours (Nh_inst_{a+1})	2,449 h	[54]
Regulatory parameters		

- Reasonable profitability (*LR*)	7.398%	[54]
- Differential added to SB_j (Δt_j)	3%	[54]
- Increase in standard operating cost (*Δ_Std_Cost*)	1%	[54]
- Standard degradation rate (K_{RR})	0.2%	[54]
- Future estimated average market price (Pmf_i)	48.75 €/MWh	[54-55]
- Second upper limit related to the deviations adjustment of Pm_i and Pmf_i ($LS2_{i,j}$)	54.04 €/MWh	[54-55]
- First upper limit related to the deviations adjustment of Pm_i and Pmf_i ($LS1_{i,j}$)	50.29 €/MWh	[54-55]
- First lower limit related to the deviations adjustment of Pm_i and Pmf_i ($LI1_{i,j}$)	42.78 €/MWh	[54-55]
- Second lower limit related to the deviations adjustment of Pm_i and Pmf_i ($LI2_{i,j}$)	39.03 €/MWh	[54-55]
Economic parameters		
- Average yield of the 10-year Spanish bonds (SB_j)	3.94%	[57]
- Consumer price index (IPC_i)	2.05%	[57]

- Average energy market price (Pm_i)	46.75 €/MWh	[58]
- Initial variable operating and maintaining cost (V_OMC_{a+1})	2.57 €/MWh	[59-61]
- Initial fixed operating costs (F_OMC_{a+1})	59.89 €/kW	[59-61]
- Tax on the produced energy (*Tax_E*)	0.5 €/MWh	[54]
- Tax on the remuneration of the produced energy (*Tax_R*)	7%	[54]
Financial parameters		
- Percentage of equity capital (*Equity*)	30%	-
- Value of the loan fixed interest rate (*Int_Rate*)	5.5%	-
- Number of years to replace the debt (*nyrd*)	15 years	-
- Percentage value of the debt opening cost (*Debt_opening_cost*)	0.5%	-
- Percentage value of the stakeholders' payment (*Stakeholders_payment*)	0%	-
- Financial cost of the debt (k_d)	6%	-
- Differential added to k_d (Δk_d)	0%	-

- Investment cost (*INV_Cost*)	6.184027 €/W	[54,60]
- Number of years for the depreciation of the asset (*nd*)	10 years	-
- Rate of corporate tax (*Tax_Rate*)	25%	-

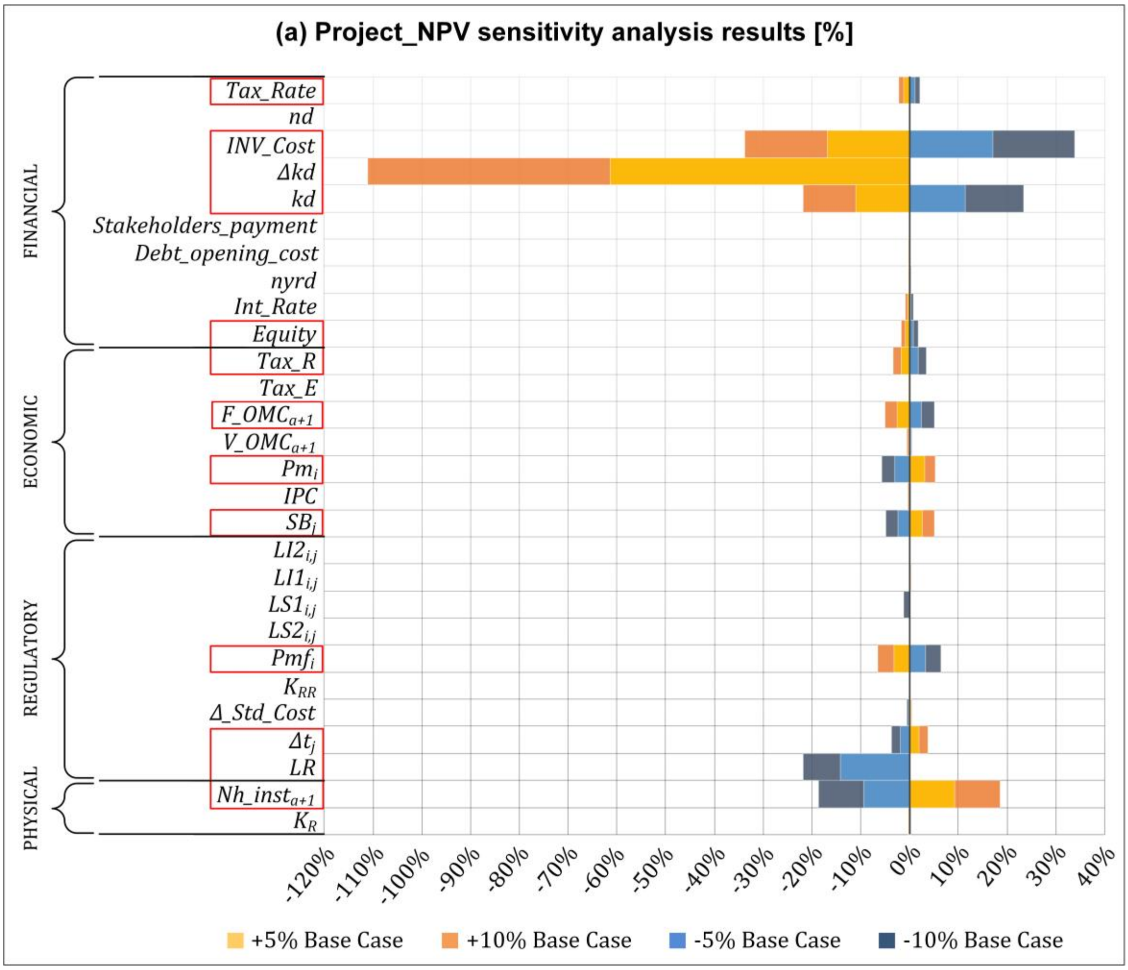
Table 3 shows the values obtained for the four economic indicators under this base case study, acting as a reference against which the sensitivity analysis results can be compared to determine the influence of each uncertain parameter in the output variables of the economic model.

Table 3. Deterministic economic results obtained under the base case scenario. Source: self-elaboration.

Economic indicators	**Base case results**
Project_NPV	81.44 M€
Project_IRR	7.59%
Project_Payback	15.60 years
Project_LCOE	236.80 €/MWh

Then, the interval of variation considered in the sensitivity analysis for each one of the “Uncertain” parameters is defined by upper and lower limits set at +10% and -10%, respectively, of its base scenario reference value (see Table 2), with intermediate steps set at ±5%. In each of the sensitivity analysis simulations, the value of a single input parameter is modified, while the rest of the parameters remain constant at the values set in the base scenario.

The results from the sensitivity analysis carried out on the twenty-eight initially identified "Uncertain" parameters are visualised in Figs. 5a-5d through four horizontal bar charts, one for each output economic metric. Warm-coloured horizontal bars represent the impact of positive variations in the input parameters with respect to the base scenario (orange-coloured for the +10% base case scenario and yellow-coloured for the +5% base case scenario). Likewise, the cold-coloured bars represent the impact caused by negative variations (dark-blue coloured for the -10% base case scenario and light-blue coloured for the -5% base case scenario)[1]. The economic impact is accounted for as a percentage of the reference results obtained in the base case study (see Table 3).



[1] Negative variations concerning the base scenario do not apply to the sensitivity analysis on two financial input parameters, Δk_d and *Stakeholders_payment*.

Fig. 5a. Sensitivity analysis results. Impact of the parameters variation on the *Project_NPV*. Source: self-elaboration.

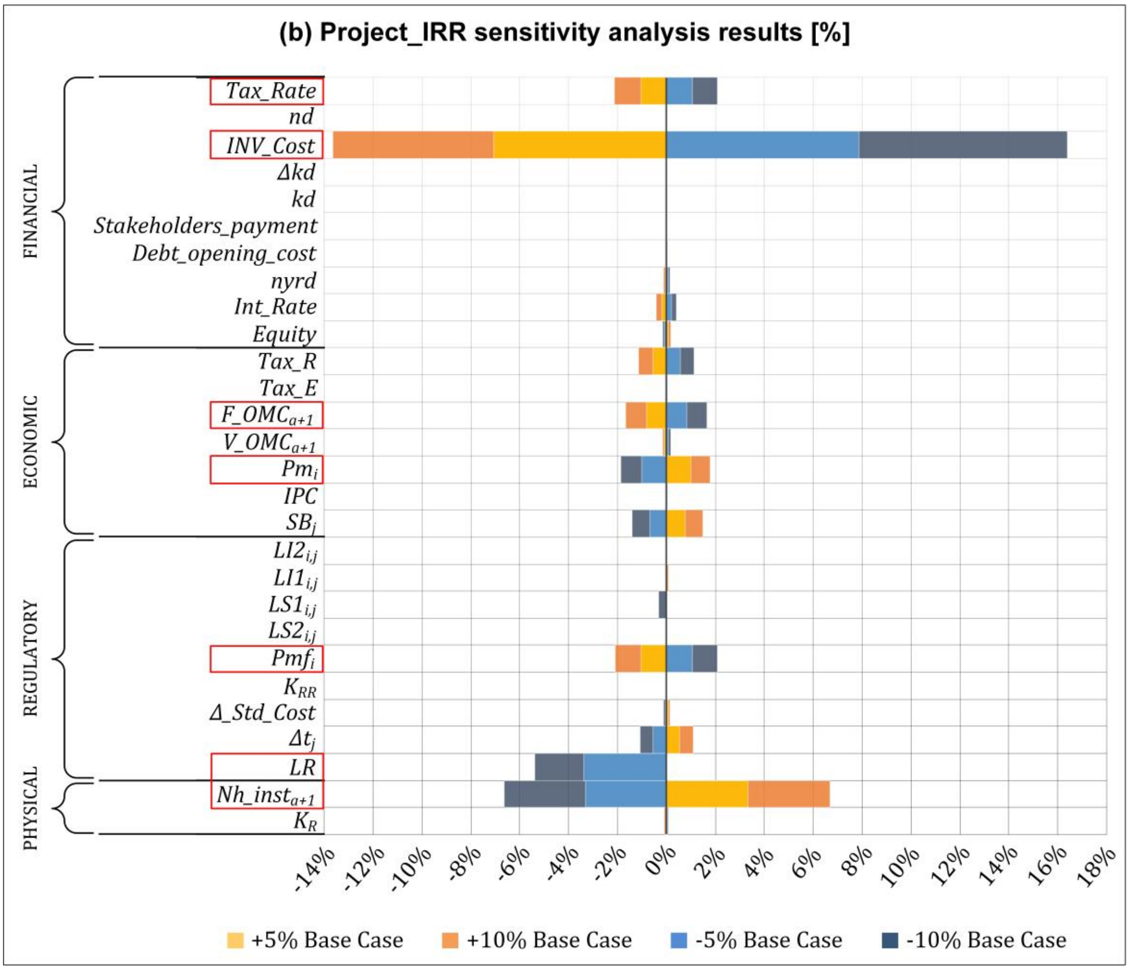


Fig. 5b. Sensitivity analysis results. Impact of the parameters variation on the *Project_IRR*. Source: self-elaboration.

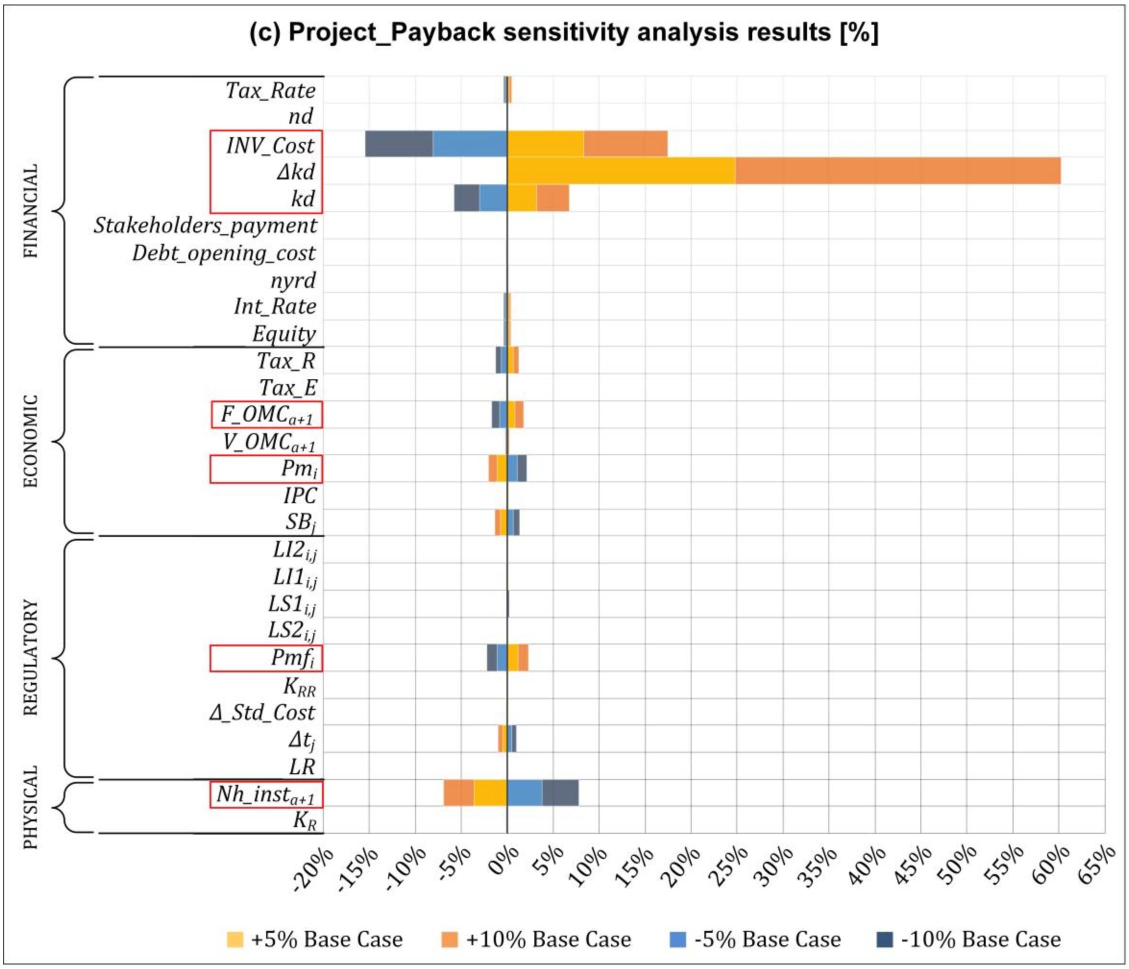


Fig. 5c. Sensitivity analysis results. Impact of the parameters variation on the *Project_Payback*. Source: self-elaboration.

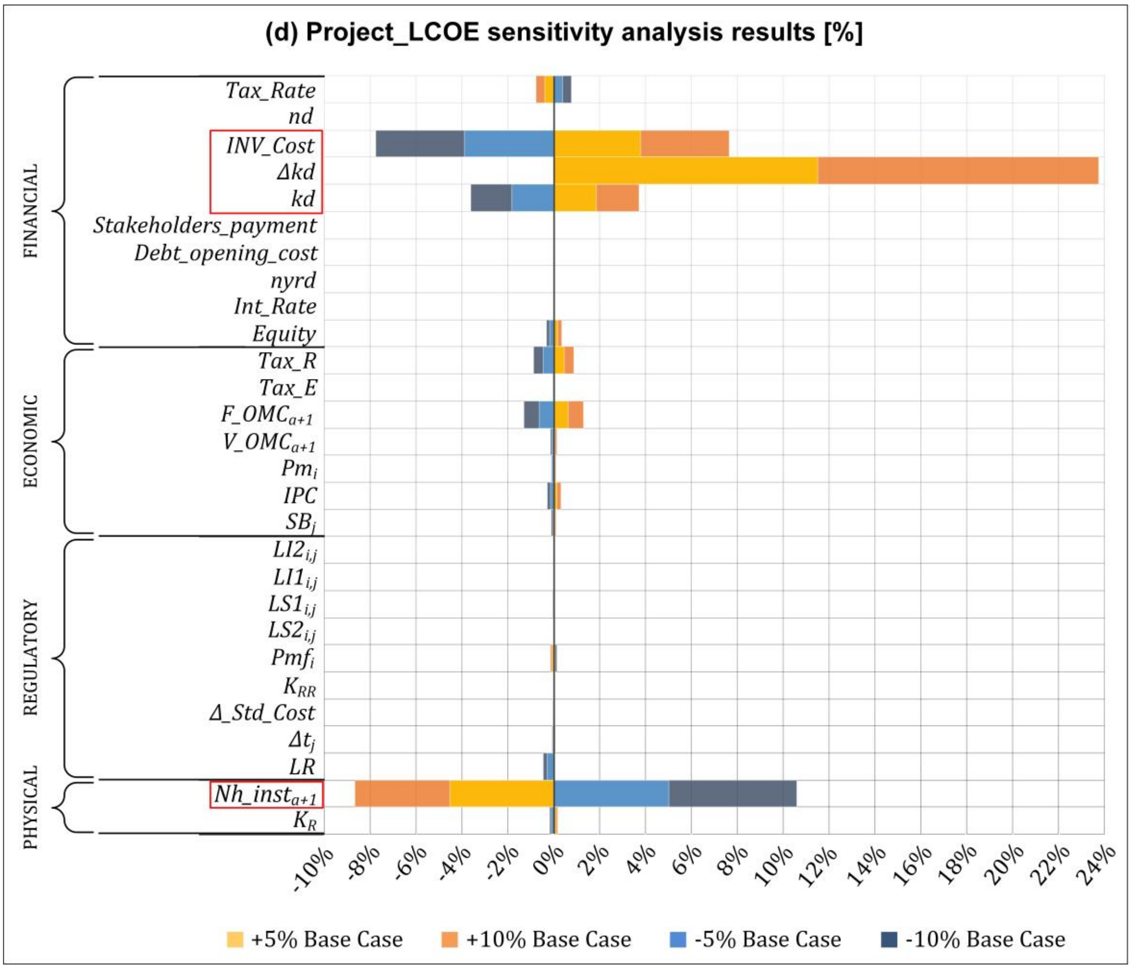


Fig. 5d. Sensitivity analysis results. Impact of the parameters variation on the *Project_LCOE*. Source: self-elaboration.

As stated above, only the uncertain parameters with significant impact on the output economic indicators would be selected as stochastic parameters for the DCF-MC analysis. In this vein, an output/input variation ratio equal to or greater than 0.15/1 has been considered as a threshold limit value of selection. Thus, all the parameters that fulfil this selection criteria are framed in red colour in Figs. 5a-5d.

According to the sensitivity results obtained (see Figs. 5a-5d), it can be concluded that the four economic indicators are quite sensitive under the defined threshold limit to variations of input parameters such as the initial number of equivalent operating hours (Nh_inst_{a+1}), which is essential for obtaining the energy generated by the CSP asset, as well as the investment cost (*INV_Cost*), due to the high capital intensity of the CSP projects. It also applies to the two paramount parameters for the calculation of the financial discount rate (*WACC*). They are the financial cost of the debt (k_d) and the differential added to k_d for determining the opportunity cost ratio of shareholders (Δk_d), except for the *Project_IRR* because of its calculation equation definition. At a second level, there are parameters such as the average energy market price (Pm_i) and the future estimated average market price (Pmf_i), as well as the initial fixed operating costs (F_OMC_{a+1}), the variation of which greatly alter the output economic indicators, with the exception of *Project_LCOE*. Finally, other parameters variation such as the reasonable profitability (*LR*) and the rate of corporate tax (*Tax_Rate*) have a considerable effect on *Project_NPV* and *Project_IRR* output variables, but not on *Project_Payback* nor on *Project_LCOE*.

In short, it has been verified the different sensitivities of each of the four economic indicators with regard to the twenty-eight “Uncertain” input parameters. On one hand, the *Project_NPV* is the one that presents a remarkable sensitivity to a greater number of parameters, specifically to thirteen of them (see Fig. 5a), since by definition its calculation implies a greater number of input parameters and intermediate calculation variables. On the other hand, the *Project_LCOE* is the least sensitive to the variation of the analysed input parameters, because of the reduced number involved in its estimation. In particular, it is only sensitive to four parameters under the set threshold value (see Fig. 5d). The sensitivity results for the *Project_IRR* and the *Project_Payback* are located halfway between the *Project_NPV and the Project_LCOE*, presenting an important impact in seven of the uncertain input parameters considered (see Fig. 5b and Fig. 5c, respectively).

5.2. Selection and characterization of stochastic parameters

Due to the substantial difference in the sensitivity of the four economic indicators with respect to the analysed “Uncertain” parameters (see the parameters framed in red colour in Figs. 5a-5d), the worst-case scenario is considered in the selection of the stochastic parameters to be taken into consideration in the DCF-MC analysis. That is, the thirteen parameters to which the *Project_NPV* is sensitive have been selected to perform the probabilistic economic analysis. In turn, the thirteen stochastic parameters are classified into the following categories: financial (38%), economic (31%), regulatory (23%), and physical (8%) (see Table 4).

Table 4 depicts the characterization of the stochastic parameters by means of the base scenario value, which is the most probable value (mode), and its variation range (minimum and maximum expected values). The definition of the variation interval has been carried out on the basis of the historical trends of each of the parameters, as well as on the evolution perspectives in the coming years.

Table 4. Characterization of the selected stochastic parameters for a CSP type facility IT-00609. Source: self-elaboration.

Parameters	**Base scenario values**	**Intervals of variation**
Physical parameters		
- Initial equivalent operating hours (Nh_inst_{a+1})	2,449 h	[1550, 3950] h
Regulatory parameters		
- Reasonable profitability (*LR*)	7.398%	[1, 8] %

- Differential added to SB_j (Δt_j)	3%	[0, 5] %
- Future estimated average market price (Pmf_i)	48.75 €/MWh	[40, 60] €/MWh
Economic parameters		
- Average yield of the 10-year Spanish bonds (SB_j)	3.94%	[1, 7] %
- Average energy market price (Pm_i)	46.75 €/MWh	[35, 65] €/MWh
- Initial fixed operating costs (F_OMC_{a+1})	59.89 €/kW	[40, 80] €/kW
- Tax on the remuneration of the produced energy (Tax_R)	7%	[0, 10] %
Financial parameters		
- Percentage of equity capital (*Equity*)	30%	[0, 50] %
- Financial cost of the debt (k_d)	6%	[5, 15] %
- Differential added to k_d (Δk_d)	0%	[0, 10] %
- Investment cost (*INV_Cost*)	6.184027 €/W	[3.5, 10.5] €/W
- Rate of corporate tax (*Tax_Rate*)	25%	[15, 35] %

In detail, the variation range for Nh_inst_{a+1} has been defined between a minimum number of 1,550 h and a maximum value of 3,950 h. The minimum value corresponds to the equivalent operating hours within the year *i* that does not entail an economic penalty in $SR\_Revenue_i$ for a

IT-00609 CSP facility type [56]. Whereas the maximum value corresponds to the limited number of reference equivalent operating hours in a year *i* established by the RD 1614/2010 [62] for the CSP facilities of parabolic trough technology with a thermal storage capacity of 7h. This value was calculated as the ratio between the annual net production in kWh and the rated power of the facility in kW.

Regarding *LR*, the variation interval ranges from a practically negligible value of 1% to a maximum value of 8%, quite close to the current value. On one hand, it is not expected that in the coming years the regulatory assigned value for *LR* can increase much more; in fact, for the next regulatory period a *LR* value of 7.09% is expected [63]. On the other hand, it has been considered the worst case as the lower limit, which would result in a *LR* close to zero set by the Government. Likewise, the variation range of Δt_j, a regulatory parameter that is closely linked to *LR*, has been adjusted in the same sense.

The intervals of variation of economic parameters such as Pm_i, Pmf_i and the average yield during determined period of the 10-year Spanish bonds in the secondary market within *j* (SB_j), have been established based on the analysis of the historical trends (maximum and minimum values) of these parameters in the last decade.

As for F_OMC_{a+1} and *INV_Cost*, their variation ranges have been set based on the maximum and the minimum values extracted from the literature analysing the evolution of the solar thermal sector costs [59-61].

Lastly, the variation intervals of financial parameters as *Equity*, k_d, Δk_d and *Tax_Rate*, as well as of the economic parameter with a regulatory assigned value *Tax_R*, have been defined based on the possible evolution of the Spanish economic-financial reality and, specifically, of the SCSPS in the forthcoming years.

5.3. Case study results

Once completed the selection and characterization of the stochastic parameters, the next step is the DCF-MC probabilistic simulation of the RD 413/2014 economic model. It consists in simultaneously varying the thirteen selected stochastic parameters in a random manner, as specified in Section 3 (see Fig. 3), using two different PDFs, i.e., uniform and triangular. In this particular case study, a total of 10,000 samples is assessed since, as observed in Fig. 6, with this number of samples the stabilization of the output results is ensured. In that way, it is guaranteed that even if the DCF-MC simulation is performed more than once, the output economic results obtained do not differ greatly from those achieved in the previous simulations. Thus, giving validity to the stochastic analysis carried out.

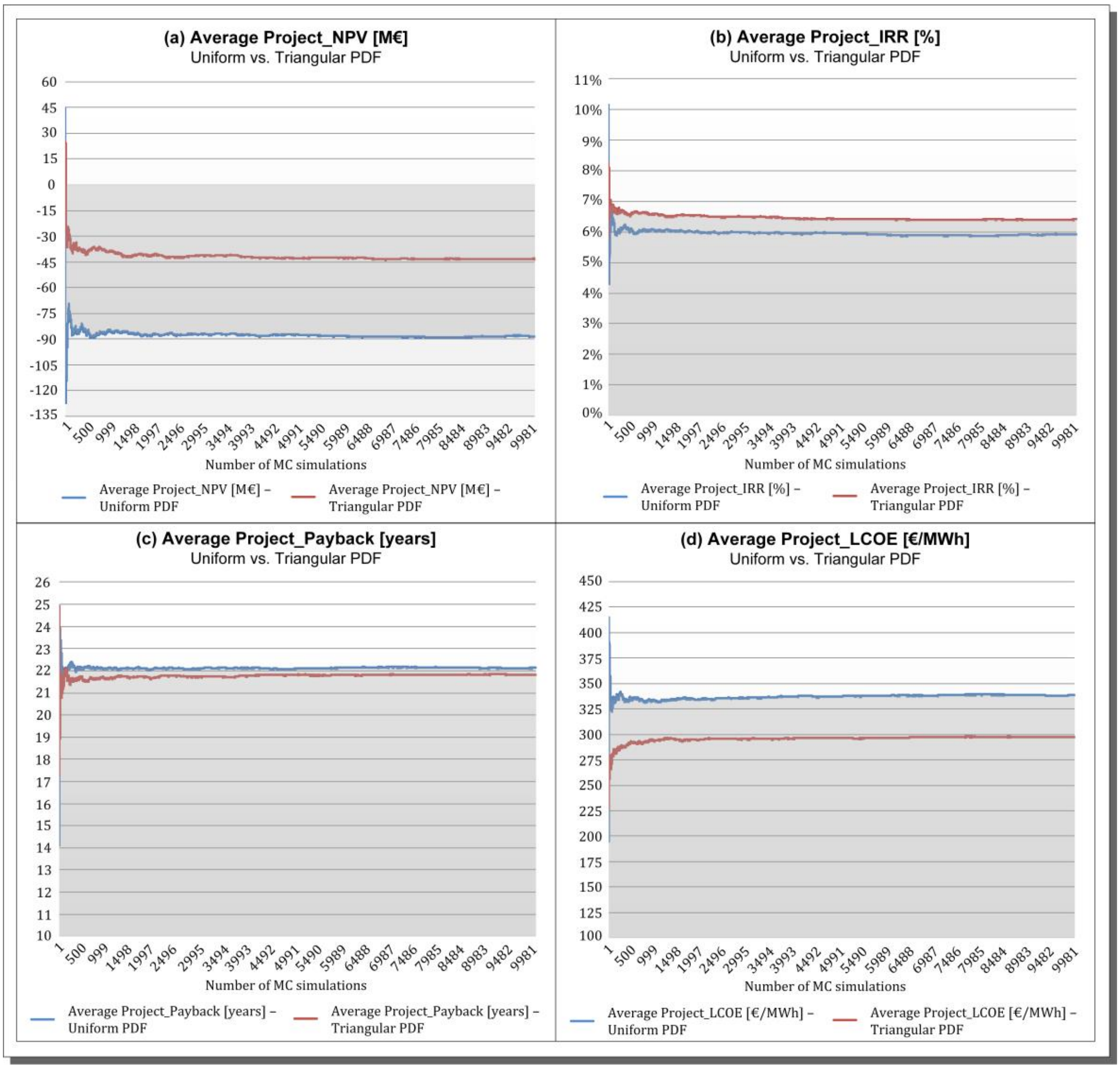


Fig. 6. Stabilization of the output variables according to the number of MC simulations. Source: self-elaboration.

On one hand, a uniform PDF is contemplated for all the stochastic parameters, where all the values in the variation range have the same probability of occurring. On the other hand, it is also considered a triangular PDF defined by a maximum and a minimum value (extremes of the variation interval), as well as by the most probable value (mode), corresponding to the base scenario value.

The uniform distribution implies that there is no knowledge about the probability of each value within the defined variation range (the worst case). The triangular distribution incorporates a certain judgment owing to the experience, and indicates the most probable value (mode) assuming a linear decrease to zero of the probability of the rest of the range values as we move away from the mode.

For a detailed summary of the results obtained for each of the four economic indicators when stochastically analysing the RD 413/2014 economic model under both uniform and triangular PDFs, see Appendix B.

6. Analysis of results

6.1. Economic valuation of the case study: MC analysis

As seen in Fig. 7, this economic analysis is performed using box diagrams. These box plots allow to analyse the probability distribution of the results in a clearer way that streamline the drawing of conclusions.

A box plot is defined by a square representing the interquartile range (IQR), that is, the distance between the first quartile (Q1 – 25th percentile) and the third quartile (Q3 – 75th percentile), and two arms called “whiskers”, which contain all the possible values of the analysed output variables. Within the box, the median (Q2 quartile – 50th percentile) is represented through a horizontal line, while the mean is marked with a cross. Regarding the whiskers, the upper whisker extends from Q3 to the upper limit (Ls), while the lower whisker extends from Q1 to the lower limit (Li). The limits Li and Ls delimit the results obtained within the range of typical observations of the sample considered. Specifically, Li is defined as the difference between the value of Q1 and 1.5 times the IQR value, while Ls is calculated as the sum of the Q3 value and 1.5 times the IQR amplitude. The results that are outside the typical observations range, called “outliers”, are considered as atypical observations and are represented, if any, with small circles (see Fig. 7).

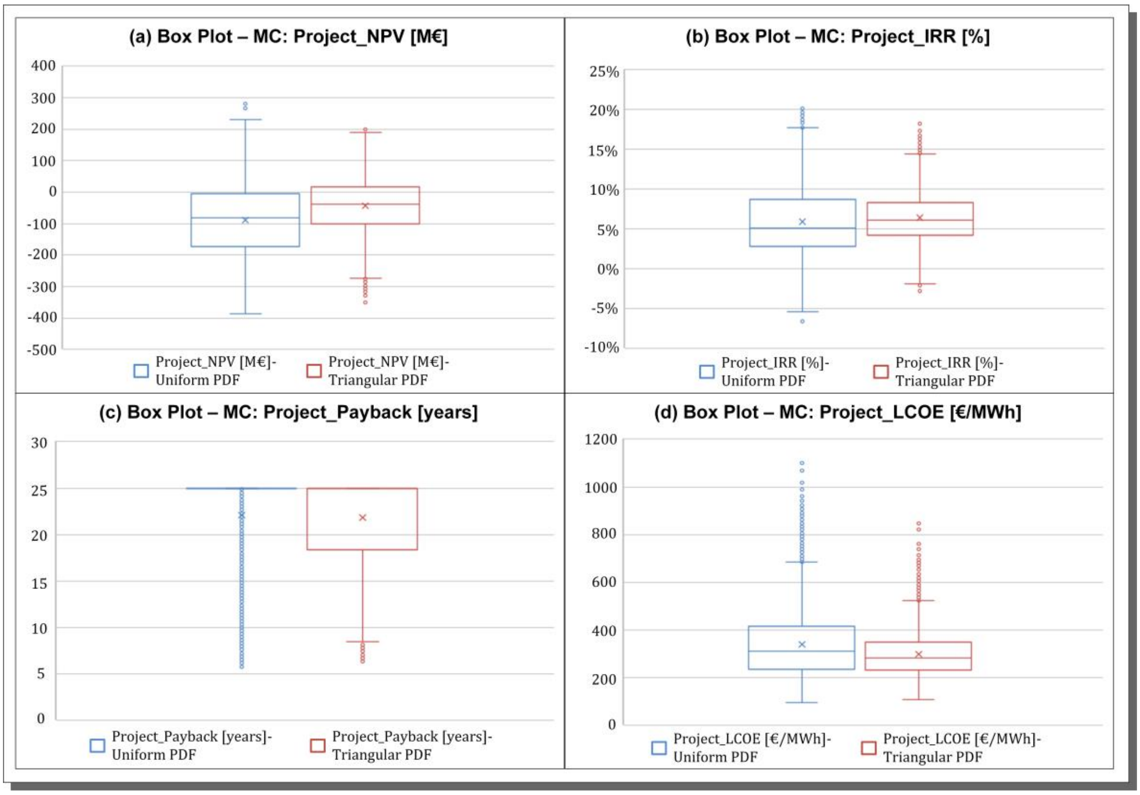


Fig. 7. MC analysis results. Impact of the stochastic parameters variation on: (a) *Project_NPV*, (b) *Project_IRR*, (c) *Project_Payback*, (d) *Project_LCOE*. Source: self-elaboration.

So, from the interpretation of these quartile-based graphs and the consideration of the most representative statistics obtained for each of the economic indicators (see Tables B.1-B.4), it is aimed to provide a set of conclusions concerning the current Spanish regulatory framework and its economic impact on the analysed energy CSP asset.

6.1.1. Regarding the project IRR and NPV

As described in [2], the retroactive RD 413/2014 regulatory framework is based on "a hypothetical efficient and well managed plant" with its "hypothetical costs". According to this, the facility here analysed has these hypothetical terms defined by the standard installation type IT-00609. The standard parameter values (see Tables 1-2), which allegedly depict the physical and economic behaviour of an "efficient plant" with the same characteristics of the CSP asset under study, are responsible for the economic results of the base case scenario (see Table 3).

Namely, according to the current regulatory framework, these "efficiently managed" facilities would see rewarded their efforts with a *Project_IRR* of 7.59%. Nevertheless, as an arbitral Award stated [64], this might be considered a fictitious value, since this regime paid no regard to "actual cost (including loan services) or actual efficiencies of specific existing CSP plants". In this regard, any deviation from these standard and unrealistic[2] values would result in a deviation in the value of the main economic indicators of the base case scenario depicted in Table 3.

In terms of *Project_IRR* value, there is an essential difference in the results obtained for both considered PDFs (see Table B.2 and Fig. 7b). On one hand, the mean of the *Project_IRR* obtained under the uniform and the triangular PDFs is 5.92% and 6.41%, respectively. In this sense, the standard deviation of the *Project_IRR* results related to the mean is 4.37% for the uniform PDF and 2.98% for the triangular one, obtaining more than 50% of the total output observations at a distance of one standard deviation from the mean. Moreover, with a 95% confidence level, it can be assured that the mean of the *Project_IRR* will be in a range between 5.83% and 6.01% for a uniform PDF, while for a triangular one, the confidence interval of the mean will be determined by the limits 6.35% and 6.47%.

[2] They could appropriately be termed as unrealistic, as it is proved in [64], because most of the standard parameters diverge from the actual parameters of CSP assets.

When comparing these results with the *Project_IRR* of the base case scenario, it can be observed that with a 50% probability the *Project_IRR* value can suffer both negative and positive variations depending on the evolution of the stochastic parameters. Thus, it is observed that the *Project_IRR* may vary from -63% to +16% for a uniform PDF, and from -45% to +10% for a triangular one. More specifically, looking at the 95% confidence interval of the mean, it can be seen reductions of between 21% and 23% under a uniform PDF, and between 15% and 16% under a triangular one.

As for the *Project_NPV*, its base case scenario value is 81.44 M€, as stated in Table 3. In turn, the values of the mean *Project_NPV* in the DCF-MC simulation for a uniform and triangular PDFs are, respectively, -88.48 M€ and -43.13 M€. In this sense, the standard deviation of the *Project_NPV* results regarding the mean is 112.33 M€ for the uniform PDF and 83.99 M€ for the triangular PDF. Besides, with a 95% confidence level it can be affirmed that the mean of the *Project_NPV* will be between -90.68 M€ and -86.28 M€ for a uniform PDF, while for a triangular one, the confidence interval of the mean will be set by the limits -44.78 M€ and -41.48 M€ (see Table B.1 and Fig. 7a). Namely, the *Project_NPV* obtained at the end of the VU of the CSP facility can be reduced between 206% and 211% under a uniform PDF, and between 151% and 155% under a triangular PDF. These results are consistent with those obtained from the analysis of *Project_IRR*, as it can be seen that a decrease in the evolution of the *Project_IRR* results in a decrease of the *Project_NPV*.

The obtained results demonstrate the importance of formulating in detail the regulatory framework and characterising the stochasticity associated with the parameters involved in the economic valuation of an energy asset. In this regard, the stochastic economic valuation has allowed quantifying how different the economic results can be in terms of project IRR and NPV between actual facilities and "standard installations" when the current Spanish regulatory framework is applied.

6.1.2. Regarding the project payback

The value of the base case scenario for the payback is 15.60 years, as depicted in Table 3. Nevertheless, the values of the *Project_Payback* mean in the DCF-MC simulation for a uniform and triangular PDFs are, respectively, 22.13 and 21.81 years. In this sense, with a 95% confidence level, it can be said that the mean of the *Project_Payback* will be in a range between 22.02 years and 22.24 years for a uniform PDF, while for a triangular one the confidence interval of the mean will be set by the limits 21.71 years and 21.91 years (see Table B.3 and Fig. 7c). Namely, it can be observed on one hand, that with a 75% probability, the payback may increase by 60% under a uniform PDF concerning the output value obtained in the base case scenario. On the other hand, under a triangular PDF, the *Project_Payback* may increase in a range between 18% and 60%. More specifically, looking at the 95% confidence interval of the mean of the *Project_Payback*, there are increases between 41% and 43% under a uniform PDF, and between 39% and 40% under a triangular one.

As previously mentioned, the regulatory framework states a 25-year regulatory life VU for the CSPP under study, which may be considered the time limit. In this regard, the results obtained stress the differences between the expectations of a "standard" and an actual CSP facility.

6.1.3. Regarding the project LCOE

As for the *Project_LCOE*, while the mean of the results obtained from the DCF-MC simulation considering a uniform PDF and a triangular one is, respectively, 338.57 €/MWh and 297.50 €/MWh, the value of the base case scenario for this economic metric is 236.80 €/MWh, as stated in Table 3. In this sense, the standard deviation of the *Project_LCOE* results concerning the mean presents a value of 142.60 €/MWh for a uniform PDF and 90 €/MWh for a triangular PDF. At a distance of one standard deviation from the mean, we have more than half of the output observations. In addition, with a 95% confidence level it can be stated that the mean of the *Project_LCOE* will be in a range between 335.78 €/MWh and 341.37 €/MWh for a uniform PDF, while for a triangular PDF the confidence interval of the mean will be established by the limits 295.73 €/MWh and 299.26 €/MWh (see Table B.4 and Fig. 7d).

Considering the base case scenario as a reference, with 50% of probability it can be seen that the *Project_LCOE* may suffer both positive and negative variations from the value obtained in the case of a "standard" facility. In this sense, the *Project_LCOE* can vary from -1% to +75% under a uniform PDF, and from -2% to +47% under a triangular one. More specifically, looking at the 95% confidence interval of the mean, it can be observed increases between 42% and 44% for a uniform PDF, and between 25% and 26% for a triangular one. Thus, when considering the actual values related to the real CSP facilities, the results prove that it is necessary to perceive a higher remuneration from the electricity market.

6.1.4. Final remarks and energy policy implications

Under the base case scenario, in which the input parameters values are aligned with the hypothetical “efficient and well-managed” CSP type facility IT-00609 set by the Government, the CSP project is economically viable at the end of its VU (see Table 3). By contrast, the probabilistic economic analysis (see Tables B.1-B.4 and Fig. 7) denotes great uncertainty and variability about the economic viability of the CSP asset subject to the evolution taken by the stochastic parameters. Even so, in general terms, there is a greater probability of having such profitability considerably reduced to the point that the CSP project turns out to be unprofitable at the end of the VU.

As noted, there is a strong probability that the *Project_NPV* may be unfavourable (*Project_NPV*<0). In the same way, as the obtained *Project_NPV* mean values are negative, it will be necessary to reduce the discount rate (WACC) of the project, resulting in smaller

Project_IRR results, in order to increase the *Project_NPV* to positive values. In the same vein, the obtained *Project_Payback* indicates a late and complicated recovery of the initial investment by the CSPP in case of obtaining it, both considering a uniform PDF and a triangular one. In the majority of the output samples, the investment cannot be recovered or it is carried out in the last years of VU of the CSP facility. Finally, the estimated *Project_LCOE* goes in the same way as the other analysed economic indicators, stressing the need to perceive a higher remuneration from the Spanish electricity market for the sale of the energy produced. This implies obtaining higher selling prices than those of the current Spanish electricity market, but taking into account the corresponding constraint. In the Spanish market there is a ceiling on the market price set at 180 €/MWh by the regulator above which energy offers cannot be made. Even so, in the last decade the average market price has been located around 50 €/MWh with maximum market prices not exceeding 160 €/MWh [58], far below the mean *Project_LCOE* values obtained in the analysis. No CSP asset would invest in the SCSPS with the economic results obtained under the current regulatory framework.

Ultimately, it can be concluded that the current RD 413/2014 framework, applied retroactively to all the existing CSPP prior to its enactment, has introduced great uncertainty and complexity into the SCSPS through the current remuneration scheme applied, as demonstrated in this analysis. This is corroborated by the fact that since the approval of this legal-economic framework, no new CSPP has been put into operation in Spain. The Spanish Government is aware of the negative impact that the current regulatory framework has had in the renewable energy sector. Consequently, it knows of the urgent need to promote the development of new renewable projects to fulfil the community and international decarbonisation commitments assumed by Spain in this matter as a part of the Paris Agreement and a Member State of the European Union [65-66].

Thus, in order to improve predictability and stability in income and financing of new electricity production facilities from renewable energy sources, the Spanish Government is trying to change this situation developing another remuneration system, additionally to the existing one, as stated in the Royal Decree-Law (RDL) 23/2020 [67]. This new remuneration scheme, based on the long-term recognition of a fixed price for energy generated, will be granted through competitive auctions [65-66].

6.2. Comparative economic valuation: uniform PDF vs. triangular PDF

It can be concluded the important variability in the four analysed economic indicators according to the variation of the input stochastic parameters in the DCF-MC simulation (see Fig. 7). This indicates the great impact of these uncertain parameters on the economic results of the CSP assets. Moreover, an important difference is observed between the results obtained when considering a uniform PDF or a triangular one (see Tables B.1-B.4 and Fig. 7). Taking into account a triangular PDF, the estimated economic results are more compact, due to the greater knowledge about the evolution of the stochastic parameters. On the other hand, considering a uniform PDF the dispersion is much greater, with more extreme output results. In addition, quite negative results are observed for the CSP assets analysed, particularly under the uniform PDF, but also under the triangular one.

Accordingly, the use of a triangular PDF to define the stochastic parameters contributes to carry out a probabilistic analysis based on a greater knowledge of the SCSPS, giving a greater probability of occurring to those scenarios more closely reflecting the current reality of this sector (namely the ones located around the mode). Whereas using a uniform PDF implies the consideration of a greater number of scenarios, including extreme cases far from the current reality of the SCSPS, with the same probability of occurring in the DCF-MC analysis. With the ultimate goal of taking into account more extreme scenarios based on historical data, to analyse what would happen under these extreme situations.

All in all, while there is a probability greater than 75% that the estimated *Project_NPV* will be negative considering a uniform PDF, this probability is reduced to 68% if the considered PDF is triangular. In both cases, the distribution of *Project_NPV* results is platykurtic (negative kurtosis) and slightly negative asymmetric, with the results quite scattered in general and more concentrated in the upper quartiles. As for the *Project_IRR*, there is almost a 6% probability that the obtained values for this economic indicator will be negative considering a uniform PDF, while taking into account a triangular PDF the loss probability is practically null. In both cases, the distribution of the *Project_IRR* results is slightly positive asymmetric, with the results more concentrated in the lower quartiles, but in the uniform PDF it is platykurtic (negative kurtosis), while in the triangular PDF it is leptokurtic (positive kurtosis). Thus, while under the uniform PDF the *Project_IRR* results are quite scattered, in the triangular PDF the results are more concentrated around the *Project_IRR* mean. With regard to the *Project_Payback*, there is a probability greater than 75% that the obtained payback period will be 25 years (or higher) considering a uniform PDF, and almost 68% if the PDF considered is triangular. In both PDFs, the distribution of the *Project_Payback* is negative asymmetric leptokurtic, with the results widely concentrated at the top of the box diagram (around the *VU* of the CSP asset) and quite scattered for small *Project_Payback* values. Finally, regarding the *Project_LCOE*, the distribution of this output economic indicator results is positive asymmetric and leptokurtic (positive kurtosis), with the results more concentrated around the *Project_LCOE* mean (at the bottom of the box diagram) and quite scattered for high values of *Project_LCOE* (see Tables B.1-B.4 and Fig. 7).

7. Conclusions

The economic feasibility of an existing CSPP in Spain has been here analysed in a probabilistic way, placing the focus on the significant impact of the uncertainty associated with the current RD 413/2014 regulatory framework on its income statement. The probabilistic analysis has been applied to the most representative case study in the Spanish CSP sector, i.e., a 50 MW CSP asset of parabolic trough technology with a TES system which obtained the operating permit in 2011. Although the results of this case study cannot be directly extrapolated to the entire SCSPP, they give an overview of the impact of the uncertainty in the mid and the long term economic valuation of these renewable energy assets. In addition, this paper provides a methodology easily replicable to other CSP technologies or renewable energy assets.

To this end, the current legal-economic framework has been firstly analysed in detail, thus demonstrating the great complexity and uncertainty that it has introduced in the economic assessment of these CSP facilities. After that, a sensitivity analysis has been carried out to determine the uncertain input parameters with more impact on the output variables of the RD 413/2014 economic model; the so-called stochastic parameters in the DCF-MC model. In this study, the *Project_NPV*, *Project_IRR*, *Project_Payback* and *Project_LCOE* have been computed as the four output variables of the model to carry out an adequate economic valuation of the CSP assets.

The sensitivity analysis simulation has disclosed the important sensitivity of the RD 413/2014 economic model to certain input parameters such as the initial number of equivalent operating hours (Nh_inst_{a+1}), the investment cost (*INV_Cost*), and the two paramount parameters in the calculation of the financial discount rate (*WACC*), that is, the financial cost of the debt (k_d) and the differential added to the financial cost of the debt (Δk_d). Obtaining for these uncertain parameters output/input variation ratios well above the defined threshold limit of 0.15/1 in most of the economic indicators analysed. Specifically, output/input variation ratios between 0.4/1 and 4/1 are obtained for these parameters, even reaching ratios of 6/1 and 11/1 for Δk_d.

Then, DCF-MC approach has been used to perform the stochastic economic assessment of the CSP case study under the Spanish RD 413/2014 framework taken into account its inherent risk. The conducted probabilistic assessment reveals considerable variability in the results, denoting a substantial uncertainty about the economic viability of these CSP facilities under the current legal-economic framework. Besides, this variability depends largely on the knowledge about the possible evolution of the stochastic parameters. Thus, it has been verified the acquisition of a more compact probability distribution of the results under a triangular PDF (which incorporates a certain judgment related to experience), than under a uniform PDF (without any knowledge about the evolution of the parameters, giving the same probability of occurring to all the values of the considered variation range). Therefore, it is vitally important to properly characterise the stochastic parameters when performing a probabilistic analysis.

Furthermore, it has been found a significant difference in the output economic metrics between the base case study here analysed based on the values established by the Spanish Government for a hypothetical “efficient and well-managed” CSP plant (deterministic case) and the reality once applying the inherent risk of the RD 413/2014 framework in the simulation (probabilistic case). Thus, under the deterministic case the CSP project is economically viable at the end of its useful life with the following values obtained for the four economic indicators: *Project_NPV* of 81.44 M€, *Project_IRR* of 7.59%, *Project_Payback* of 15.60 years and *Project_LCOE* of 236.80 €/MWh. Whereas, the results obtained under the probabilistic analysis show quite substantial profitability reductions in the income statement of the CSP case study with both considered PDFs. By way of example, the mean values of the four economic indicators analysed may vary with respect to the deterministic case results in the following way considering a uniform and a triangular PDF respectively: -209% and -153% for *Project_NPV*, -22% and -16% for *Project_IRR*, +42% and +40% for *Project_Payback*, and +43% and +26% for *Project_LCOE*. Accordingly, there is a high probability of obtaining negative *Project_NPV* values, specifically 75% under a uniform PDF and 68% under a triangular PDF, seriously affecting the *Project_IRR* results. This in turn results in high values of *Project_Payback* (very close or higher than the useful life of the CSP facility) as well as of *Project_LCOE*.

In short, this paper has firstly demonstrated that the economic valuation models cannot be turned away from the existing country-specific regulatory reality and its possible inherent risk. In the Spanish case, it is clear that the RD 413/2014 framework, which regulates the CSP sector as well as the other renewable energy sectors, must move towards a more simplified, stable and predictable model providing the maximum legal-economic security to investors.

Moreover, it has been verified the high relevance of carrying out a probabilistic study for improving the decision-making process in the management of the CSPP under legal-economic frameworks with a high degree of uncertainty and inherent risk, as in the Spanish case. Solely by carrying out a deterministic analysis, it would not have allowed to take into account and assess the enormous impact of the uncertainty associated with the RD 413/2014 stochastic parameters in the income statement of the SCSPP. Obviously, each country has its own regulation regarding renewable energy. Here is the difficult of analysing the legal-economic reality of each country and adapting the models to the country-specific energy policy.

Acknowledgements

The authors are especially grateful to all those persons and companies from the SCSPS who (confidentially and anonymously) have contributed to a better understanding of the CSPP reality in Spain. This work was supported by the Ministry of Science, Innovation and Universities of Spain and by the European Regional Development Fund under project RTI2018-100732-B-C22; and by the Agència de Gestió d'Ajuts Universitaris i de Recerca (AGAUR) and the European Social Fund grant for universities, research centers and hospital foundations to hire new research staff (FI) [grant number 2018FI_B_00755 and 2019FI_B1_00077].

References

[1] REN21. Renewables 2019. Global status report; 2019. [Online]. Available: https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf [accessed August 2019].

[2] de la Hoz, J., Martín, H., Montalà, M., Matas, J., Guzman, R., 2018. Assessing the 2014 retroactive regulatory framework applied to the concentrating solar power systems in Spain. Applied Energy. 212, 1377–1399. https://doi.org/10.1016/j.apenergy.2018.01.012.

[3] Hernández-Moro, J., Martínez-Duart, J.M., 2012. CSP electricity cost evolution and grid parities based on the IEA roadmaps. Energy Policy 41, 184–192. https://doi.org/10.1016/j.enpol.2011.10.032.

[4] Hernández-Moro, J., Martínez-Duart, J.M., 2013. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renewable and Sustainable Energy Reviews 20, 119-132. https://doi.org/10.1016/j.rser.2012.11.082.

[5] Domínguez, R., Conejo, A.J., Carrión, M., 2014. Operation of a fully renewable electric energy system with CSP plants. Applied Energy 119, 417–430. https://doi.org/10.1016/j.apenergy.2014.01.014.

[6] Pousinho, H.M.I., Silva, H., Mendes, V.M.F., Collares-Pereira, M., Pereira Cabrita, C., 2014. Self-scheduling for energy and spinning reserve of wind/CSP plants by a MILP approach. Energy 78, 524–534. https://doi.org/10.1016/j.energy.2014.10.039.

[7] Dowling, A.W., Zheng, T., Zavala, V.M., 2017. Economic assessment of concentrated solar power technologies: A review. Renewable and Sustainable Energy Reviews. 72, 1019–1032. https://doi.org/10.1016/j.rser.2017.01.006.

[8] Haneklaus, N., Schröders, S., Zheng, Y., Allelein, H-J., 2017. Economic evaluation of flameless phosphate rock calcination with concentrated solar power and high temperature reactors. Energy. 140, 1148–1157. https://doi.org/10.1016/j.energy.2017.08.123.

[9] Hinkley, J.T., Hayward, J.A., Curtin, B., Wonhas, A., Boyd, R., Grima, C., Tadros, A., Hall, R., Naicker, K., 2013. An analysis of the costs and opportunities for

concentrating solar power in Australia. Renewable Energy. 57, 653-661. https://doi.org/10.1016/j.renene.2013.02.020.

[10] Zhao, Y., Hong, H., Jin, H., 2016. Appropriate feed-in tariff of solar-coal hybrid power plant for China's Inner Mongolia Region. Applied Thermal Engineering. 108, 378–387. https://doi.org/10.1016/j.applthermaleng.2016.07.062.

[11] Ling-zhi, R., Xin-gang, Z., Yu-zhuo, Z., Yan-bin, L., 2018. The economic performance of concentrated solar power industry in China. Journal of Cleaner Production. 205, 799–813. https://doi.org/10.1016/j.jclepro.2018.09.110.

[12] Ji, J., Tang, H., Jin, P., 2019. Economic potential to develop concentrating solar power in China: A provincial assessment. Renewable and Sustainable Energy Reviews. 114, 109279. https://doi.org/10.1016/j.rser.2019.109279.

[13] Indora, S., Kandpal, T.C., 2019. Financial appraisal of using Scheffler dish for steam based institutional solar cooking in India. Renewable Energy. 135, 1400-1411. https://doi.org/10.1016/j.renene.2018.09.067.

[14] Sharma, C., Sharma, A.K., Mullick, S.C., Kandpal, T.C., 2018. Cost reduction potential of parabolic trough based concentrating power plants in India. Energy for Sustainable Development. 42, 121-128. https://doi.org/10.1016/j.esd.2017.10.003.

[15] Brand, B., Boudghene Stambouli, A., Zejli, D., 2012. The value of dispatchability of CSP plants in the electricity systems of Morocco and Algeria. Energy Policy 47, 321–331. https://doi.org/10.1016/j.enpol.2012.04.073.

[16] Schinko, T., Komendantova, N., 2016. De-risking investment into concentrated solar power in North Africa: Impacts on the costs of electricity generation. Renewable Energy. 92, 262–272. https://doi.org/10.1016/j.renene.2016.02.009.

[17] Simsek, Y., Mata-Torres, C., Guzmán, A.M., Cardemil, J.M., Escobar, R., 2018. Sensitivity and effectiveness analysis of incentives for concentrated solar power projects in Chile. Renewable Energy. 129, 214–224. https://doi.org/10.1016/j.renene.2018.06.012.

[18] Servert, J.F., Cerrajero, E., Fuentealba, E.L., Greos, S., 2015. Feasibility of a CSP power plant in Chile under a PPA model, the role of soft financing and upfront grant. Energy Procedia. 69, 1704-1710. https://doi.org/10.1016/j.egypro.2015.03.133.

[19] Mahia, R., De Arce, R., Medina, E., 2014. Assessing the future of a CSP industry in Morocco. Energy Policy 69, 586–597. https://doi.org/10.1016/j.enpol.2014.02.024.

[20] Heck, H., Smith, C., Hittinger, E., 2016. A Monte Carlo approach to integrating uncertainty into the levelized cost of electricity. The Electricity Journal. 29, 21-30. https://doi.org/10.1016/j.tej.2016.04.001.

[21] Barros, J.J.C., Coira, M.L., de la Cruz López, M.P., del Caño Gochi, A., 2016. Probabilistic life-cycle cost analysis for renewable and non-renewable power plants. Energy. 112, 774-787. https://doi.org/10.1016/j.energy.2016.06.098.

[22] Tran, T.T.D., Smith, A.D., 2018. Incorporating performance-based global sensitivity and uncertainty analysis into LCOE calculations for emerging renewable energy technologies. Applied Energy. 216, 157-171. https://doi.org/10.1016/j.apenergy.2018.02.024.

[23] Ho, C., Mehos, M., Turchi, C., Wagner, M., 2014. Probabilistic analysis of power tower systems to achieve SunShot goals. Energy Procedia. 49, 1410-1419. https://doi.org/10.1016/j.egypro.2014.03.150.

[24] De Luca, F., Ferraro, V., Marinelli, V., 2015. On the performance of CSP oil-cooled plants, with and without heat storage in tanks of molten salts. Energy 83, 230–239. https://doi.org/10.1016/j.energy.2015.02.017.

[25] Yilmazoglu, M., 2016. Effects of the selection of heat transfer fluid and condenser type on the performance of a solar thermal power plant with technoeconomic approach. Energy Conversion and Management. 111, 271–278. https://doi.org/10.1016/j.enconman.2015.12.068.

[26] Wang, F., Li, H., Zhao, J., Deng, S., Yan, J., 2016. Technical and economic analysis of integrating low-medium temperature solar energy into power plant. Energy Conversion and Management. 112, 459–469. https://doi.org/10.1016/j.enconman.2016.01.037.

[27] Pearce, M., Shemfe, M., Sansom, C., 2016. Techno-economic analysis of solar integrated hydrothermal liquefaction of microalgae. Applied Energy. 166, 19–26. https://doi.org/10.1016/j.apenergy.2016.01.005.

[28] Martinek, J., Jorgenson, J., Mehos, M., Denholm, P., 2018. A comparison of price-taker and production cost models for determining system value, revenue, and scheduling of concentrating solar power plants. Applied Energy. 231, 854–865. https://doi.org/10.1016/j.apenergy.2018.09.136.

[29] McTigue, J.D., Castro, J., Mungas, G., Kramer, N., King, J., Turchi, C., Zhu, G., 2018. Hybridizing a geothermal power plant with concentrating solar power and thermal storage to increase power generation and dispatchability. Applied Energy. 228, 1837–1852. https://doi.org/10.1016/j.apenergy.2018.07.064.

[30] Lim, J.H., Dally, B.B., Chinnici, A., Nathan, G.J., 2017. Techno-economic evaluation of modular hybrid concentrating solar power systems. Energy. 129, 158–170. https://doi.org/10.1016/j.energy.2017.04.067.

[31] Meybodi, M.A., Beath, A.C., 2016. Impact of cost uncertainties and solar data variations on the economics of central receiver solar power plants: an Australian case study. Renewable Energy. 93, 510–524. https://doi.org/10.1016/j.renene.2016.03.016.

[32] Du, E., Zhang, N., Hodge, B-M., Kang, C., Kroposki, B., Xia, Q., 2018. Economic justification of concentrating solar power in high renewable energy penetrated power systems. Applied Energy. 222, 649–661. https://doi.org/10.1016/j.apenergy.2018.03.161.

[33] Wang, A., Han, X., Liu, M., Yan, J., Liu, J., 2019. Thermodynamic and economic analyses of a parabolic trough concentrating solar power plant under off-design conditions. Applied Thermal Engineering. 156, 340-350. https://doi.org/10.1016/j.applthermaleng.2019.04.062.

[34] Trabelsi, S.E., Chargui, R., Qoaider, L., Liqreina, A., Guizani, A., 2016. Techno-economic performance of concentrating solar power plants under the climatic conditions of the southern region of Tunisia. Energy Conversion and Management. 119, 203–214. https://doi.org/10.1016/j.enconman.2016.04.033.

[35] Kost, C., Engelken, M., Schlegl, T., 2012. Value generation of future CSP projects in North Africa. Energy Policy 46, 88–99. https://doi.org/10.1016/j.enpol.2012.03.034.

[36] Bendato, I., Cassettari, L., Mosca, M., Mosca, R., 2016. Stochastic techno-economic assessment based on Monte Carlo simulation and the Response Surface

Methodology: The case of an innovative linear Fresnel CSP (concentrated solar power) system. Energy 101, 309–324. https://doi.org/10.1016/j.energy.2016.02.048.

[37] Corona, B., Cerrajero, E., López, D., San Miguel, G., 2016. Full environmental life cycle cost analysis of concentrating solar power technology: Contribution of externalities to overall energy costs. Solar Energy. 135, 758–768. https://doi.org/10.1016/j.solener.2016.06.059.

[38] Corral, N., Anrique, N., Fernandes, D., Parrado, C., Cáceres, G., 2012. Power, placement and LEC evaluation to install CSP plants in northern Chile. Renewable and Sustainable Energy Reviews 16, 6678–6685. https://doi.org/10.1016/j.rser.2012.09.006.

[39] Kassem, A., Al-Haddad, K., Komljenovic, D., 2017. Concentrated solar thermal power in Saudi Arabia: Definition and simulation of alternative scenarios. Renewable and Sustainable Energy Reviews. 80, 75–91. https://doi.org/10.1016/j.rser.2017.05.157.

[40] Fritsch, A., Frantz, C., Uhlig, R., 2019. Techno-economic analysis of solar thermal power plants using liquid sodium as heat transfer fluid. Solar Energy. 177, 155–162. https://doi.org/10.1016/j.solener.2018.10.005.

[41] Aly, A., Bernardos, A., Fernandez-Peruchena, C.M., Jensen, S.S., Pedersen, A.B., 2018. Is Concentrated Solar Power (CSP) a feasible option for Sub-Saharan Africa?: Investigating the techno-economic feasibility of CSP in Tanzania. Renewable Energy. 1–17. https://doi.org/10.1016/j.renene.2018.09.065.

[42] Islam, M.T., Huda, N., Saidur, R., 2019. Current energy mix and techno-economic analysis of concentrating solar power (CSP) technologies in Malaysia. Renewable Energy. 140, 789-806. https://doi.org/10.1016/j.renene.2019.03.107.

[43] Vose, D. Risk Analysis: A quantitative guide. 3rd ed. John Wiley & Sons, Ltd. 2008.

[44] Kathleen, M. (2013). Flexible Design: An Innovative Approach for Planning Water Infrastructure Systems Under Uncertainty (Master of Science in Technology and Policy). Massachusetts Institute of Technology.

[45] Ioannou, A., Angus, A., Brennan, F., 2017. Risk-based methods for sustainable energy system planning: A review. Renewable and Sustainable Energy Reviews. 74, 602-615. https://doi.org/10.1016/j.rser.2017.02.082.

[46] Usaola, J., 2012. Participation of CSP plants in the reserve markets: A new challenge for regulators. Energy Policy 49, 562–571. https://doi.org/10.1016/j.enpol.2012.06.060.

[47] Martín, H., De La Hoz, J., Velasco, G., Castilla, M., García De Vicuña, J.L., 2015. Promotion of concentrating solar thermal power (CSP) in Spain: Performance analysis of the period 1998-2013. Renewable and Sustainable Energy Reviews. 50, 1052–1068. https://doi.org/10.1016/j.rser.2015.05.062.

[48] Williges, K., Lilliestam, J., Patt, A., 2010. Making concentrated solar power competitive with coal: The costs of a European feed-in tariff. Energy Policy 38(6), 3089-3097. https://doi.org/10.1016/j.enpol.2010.01.049.

[49] San Miguel, G., Corona, B., 2018. Economic viability of concentrated solar power under different regulatory frameworks in Spain. Renewable and Sustainable Energy Reviews. 91, 205–218. https://doi.org/10.1016/j.rser.2018.03.017.

[50] de la Hoz, J., Martín, H., Miret, J., Castilla, M., Guzman, R., 2016. Evaluating the 2014 retroactive regulatory framework applied to the grid connected PV systems in Spain. Applied Energy. 170, 329–344. https://doi.org/10.1016/j.apenergy.2016.02.092.

[51] de la Hoz, J., Martín, H., Ballart, J., Monjo, L., 2014. Evaluating the approach to reduce the overrun cost of grid connected PV systems for the Spanish electricity sector: Performance analysis of the period 2010-2012. Applied Energy. 121, 159-173. https://doi.org/10.1016/j.apenergy.2014.01.083.

[52] de la Hoz, J., Martín, H., Alonso, A., Luna, A.C., Matas, J., Vasquez, J.C., Guerrero, J.M., 2019. Regulatory-framework-embedded energy management system for microgrids: The case study of the Spanish self-consumption scheme. Applied Energy. 251, 113374. https://doi.org/10.1016/j.apenergy.2019.113374.

[53] Law 24/2013, of 26 December. BOE no. 310, December 27, 2013. [Online]. Available: https://www.boe.es/buscar/act.php?id=BOE-A-2013-13645 [accessed July 2019].

[54] MO IET/1045/2014, of 16 June. BOE no. 150, June 20, 2014. [Online]. Available: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2014-6495 [accessed June 2019].

[55] MO ETU/130/2017, of 17 February. BOE no. 45, February 22, 2017. [Online]. Available: https://www.boe.es/buscar/doc.php?id=BOE-A-2017-1793 [accessed June 2019].

[56] RD 413/2014, of 6 June. BOE no. 140, June 10, 2014. [Online]. Available: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2014-6123 [accessed June 2019].

[57] Instituto Nacional de Estadística. INEbase. [Online]. Available: https://www.ine.es/dyngs/INEbase/listaoperaciones.htm [accessed July 2019].

[58] OMIE. Resultados del mercado. [Online]. Available: http://www.omie.es/files/flash/ResultadosMercado.html# [accessed July 2019].

[59] Plan de energías renovables en España 2011-2020. Ministerio de Industria, Turismo y Comercio. Instituto para la Diversificación y Ahorro de la Energía, IDAE. Madrid, 2011. [Online]. Available: https://www.idae.es/tecnologias/energias-renovables/plan-de-energias-renovables-2011-2020 [accessed July 2019].

[60] Jordan D.C., Kurtz, S.R. Photovoltaic Degradation Rates – An Analytical Review. Journal Article NREL/JA-5200-51664. National Renewable Energy Laboratory, June 2012. [Online]. Available: https://www.nrel.gov/docs/fy12osti/51664.pdf [accessed July 2019].

[61] Renewable Energy Technologies: Cost Analysis Series. Concentrating Solar Power. Volume 1: Power Sector, Issue 2/5. International Renewable Energy Agency, June 2012. [Online]. Available: https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf [accessed July 2019].

[62] RD 1614/2010, of 7 December. BOE no. 298, December 8, 2010. [Online]. Available: https://www.boe.es/buscar/doc.php?id=BOE-A-2010-18915 [accessed June 2019].

[63] Ley de Tasas de Retribución Electricidad. Ministerio para la Transición Ecológica. Madrid, 2019. [Online]. Available: https://www.miteco.gob.es/es/ministerio/servicios/participacion-publica/Ley_de_Tasas_de_Retribucion_Electricidad.aspx [accessed July 2019].

[64] ICSID Case No. ARB/13/36. [Online]. Available: http://www.energycharter.org/fileadmin/DocumentsMedia/Disputes/ISDSC-043en.pdf. [accessed August 2019].

[65] El MITECO inicia la tramitación del proyecto de Real Decreto de subastas de energías renovables. Ministerio para la Transición Ecológica y el Reto Demográfico.

Madrid, 2020. [Online]. Available: https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-miteco-inicia-la-tramitaci%C3%B3n-del-proyecto-de-real-decreto-de-subastas-de-energ%C3%ADas-renovables/tcm:30-510161 [accessed August 2020].

[66] Proyecto de Real Decreto por el que se regula el Régimen Económico de Energías Renovables para instalaciones de Producción de Energía Eléctrica. Ministerio para la Transición Ecológica y el Reto Demográfico. Madrid, 2020. [Online]. Available: https://energia.gob.es/es-es/Participacion/Paginas/DetalleParticipacionPublica.aspx?k=324 [accessed August 2020].

[67] RDL 23/2020, of 23 June. BOE no. 175, June 24, 2020. [Online]. Available: https://www.boe.es/buscar/act.php?id=BOE-A-2020-6621&p=20200624&tn=1#a2 [accessed August 2020].

Appendix A. Economic model formulation

Physical and remuneration scheme

$$Revenue_i = Market\_Revenue_i + SR\_Revenue_i \quad \text{(A.1)}$$

$$Market\_Revenue_i = E_i \cdot Pm_i \quad \text{(A.2)}$$

$$E_i = P_n \cdot Nh\_inst_i \quad \text{(A.3)}$$

$$Nh\_inst_i = Nh\_inst_{a+1} \cdot \left[1 - K_R \cdot \left(i - (a+1)\right)\right], \quad i \geq a+1 \quad \text{(A.4)}$$

$$SR\_Revenue_i = (Op\_R_i + Inv\_R_i) \cdot d_i \quad \text{(A.5)}$$

$$d_i = \begin{cases} 1 & Nh\_inst_i > Nh\_min_i \\ \dfrac{Nh\_inst_i - Uf_i}{Nh\_min_i - Uf_i} & Uf_i \leq Nh\_inst_i \leq Nh\_min_i \\ 0 & Uf_i > Nh\_inst_i \end{cases} \quad \text{(A.6)}$$

$$Op\_R_i = \begin{cases} E_i \cdot Ro_i, & E_i \leq E\_max_i \\ E\_max_i \cdot Ro_i, & E_i > E\_max_i \end{cases} \quad \text{(A.7)}$$

$$E\_max_i = P_n \cdot Nh\_max_{(R_o)i} \quad \text{(A.8)}$$

$$Ro_i = C\_Eexpf_i - Pmf_i \quad \text{(A.9)}$$

$$C\_Eexpf_i = C\_Eexpf_{2014} \cdot (1 + \Delta\_Std\_Cost)^{(i-2014)} \quad \text{(A.10)}$$

$$Inv\_R_i = P_n \cdot Rinv_{j,a} \quad \text{(A.11)}$$

$$Rinv_{j,a} = \begin{cases} C_{j,a} \cdot VNA_{j,a} \cdot K_j, & PT\_IRR_i \leq LR \\ 0, & PT\_IRR_i > LR \end{cases} \quad \text{(A.12)}$$

$$C_{j,a} = \frac{VNA_{j,a} - \sum_{i=p}^{a+VU} \dfrac{(Ingf_i - Cexpf_i)}{(1+t_j)^{i-p+1}}}{VNA_{j,a}} \quad \text{(A.13)}$$

$$Ingf_i = (Pmf_i + Ro_i) \cdot Nh_{i,j} \quad \text{(A.14)}$$

$$Cexpf_i = C\_Eexpf_i \cdot Nh_{i,j} \quad \text{(A.15)}$$

$$Nh_{i,j} = Nh_{2014} \cdot (1 - K_{RR})^{(i-2014)} \quad \text{(A.16)}$$

$$VNA_{j,a} = \begin{cases} VI_a \cdot (1+t_j)^{p-a-1} - \sum_{i=a+1}^{p-1} (Ing_i - Cexp_i) \cdot (1+t_j)^{p-i-1}, & j = 1 \\ VNA_{j-1,a} \cdot (1+t_{j-1})^{sm} - \sum_{i=p-sm}^{p-1} (Ingf_{i,j-1} - Cexpf_{i,j-1} - Vajdm_{i,j-1}) \cdot (1+t_{j-1})^{p-i-1}, & j > 1 \end{cases} \tag{A.17}$$

$$Ing_i = Pm\_e_i \cdot Nh\_e_i \tag{A.18}$$

$$Cexp_i = C\_Eexp\_e_i \cdot Nh\_e_i \tag{A.19}$$

$$Vajdm_{i,j} = \begin{cases} Nh_{i,j} \cdot 0{,}5 \cdot (LS1_{i,j} - LS2_{i,j}) + Nh_{i,j} \cdot (LS2_{i,j} - Pm_i), & Pm_i > LS2_{i,j} \\ Nh_{i,j} \cdot 0{,}5 \cdot (LS1_{i,j} - Pm_i), & LS1_{i,j} \le Pm_i \le LS2_{i,j} \\ 0, & LI1_{i,j} \le Pm_i \le LS1_{i,j} \\ Nh_{i,j} \cdot 0{,}5 \cdot (LI1_{i,j} - Pm_i), & LI2_{i,j} \le Pm_i \le LI1_{i,j} \\ Nh_{i,j} \cdot 0{,}5 \cdot (LI1_{i,j} - LI2_{i,j}) + Nh_{i,j} \cdot (LI2_{i,j} - Pm_i), & Pm_i < LI2_{i,j} \end{cases} \tag{A.20}$$

$$t_j = SB_j + \Delta t_j \tag{A.21}$$

$$K_j = \frac{t_j \cdot (1+t_j)^{VR_j}}{(1+t_j)^{VR_j} - 1} \tag{A.22}$$

Operating cost scheme

$$Operating\_Cost_i = Fixed\_OMC_i + Variable\_OMC_i + ETax\_Cost_i + RTax\_Cost_i \tag{A.23}$$

$$Fixed\_OMC_i = F\_OMC_i \cdot P_n \tag{A.24}$$

$$F\_OMC_i = F\_OMC_{a+1} \cdot (1 + IPC)^{i-(a+1)} \tag{A.25}$$

$$Variable\_OMC_i = V\_OMC_i \cdot E_i \tag{A.26}$$

$$V\_OMC_i = V\_OMC_{a+1} \cdot (1 + IPC)^{i-(a+1)} \tag{A.27}$$

$$ETax\_Cost_i = Tax\_E \cdot E_i, \quad 2011 \leq i \leq a + VU \tag{A.28}$$

$$RTax\_Cost_i = Tax\_R \cdot Revenue_i, \quad 2013 \leq i \leq a + VU \tag{A.29}$$

Income statement scheme

$$Project\_NPV = -P_n \cdot INV\_Cost + \sum_{i=a+1}^{a+VU} \frac{Project\_CashFlow_i}{(1 + WACC)^{i-a}} \tag{A.30}$$

$$-P_n \cdot INV\_Cost + \sum_{i=a+1}^{a+VU} \frac{Project\_CashFlow_i}{(1 + Project\_IRR)^{i-a}} = 0 \tag{A.31}$$

$$Project\_Payback = lp + \frac{P_n \cdot INV\_Cost - \sum_{i=a+1}^{lp} \frac{Project\_CashFlow_i}{(1 + WACC)^{i-a}}}{\frac{Project\_CashFlow_{ir}}{(1 + WACC)^{ir-a}}} \tag{A.32}$$

$$Project\_LCOE = \frac{P_n \cdot INV\_Cost + \sum_{i=a+1}^{a+VU} \frac{Operating\_Cost_i}{(1 + WACC)^{i-a}}}{\sum_{i=a+1}^{a+VU} \frac{E_i}{(1 + WACC)^{i-a}}} \tag{A.33}$$

$$WACC = Equity \cdot (k_d + \Delta k_d) + (1 - Equity) \cdot k_d \cdot (1 - Tax\_Rate) \tag{A.34}$$

Appendix B. Detailed results obtained from the Monte Carlo simulation of the case study

Project_NPV

Table B.1. Representative statistics from the *Project_NPV* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

	Probability Distribution	
Statistics – Project_NPV [€]	**Uniform**	**Triangular**
Mean [M€]	-88.48	-43.13
Typical error [M€]	1.12	0.84
Median [M€]	-82.61	-39.11
Mode [M€]	-	2.41
Standard Deviation [M€]	112.33	83.99
Variance [M€^{2}]	12,618,714,145.29	7,053,488,650.05
Kurtosis	-0.65	-0.25
Asymmetry	-0.07	-0.19
Range [M€]	667.57	558.75
Minimum [M€]	-386.23	-350.77
Maximum [M€]	281.34	207.97
Sample Total number	10,000	10,000
Loss probability [%]	76.27%	67.85%
Confidence interval (acceptance level 95%) [M€]	2.20	1.65

Project_IRR

Table B.2. Representative statistics from the *Project_IRR* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

	Probability Distribution	
Statistics – Project_IRR [%]	**Uniform**	**Triangular**
Mean [%]	5.92	6.41
Typical error [%]	0.04	0.03
Median [%]	5.17	6.15
Mode [%]	-	9.42
Standard Deviation [%]	4.37	2.98
Variance [$\%^2$]	0.19	0.09
Kurtosis	-0.13	0.07
Asymmetry	0.51	0.43
Range [%]	26.68	20.94
Minimum [%]	-6.56	-2.73
Maximum [%]	20.12	18.21
Sample Total number	10,000	10,000
Loss probability [%]	5.94	0.72
Confidence interval (acceptance level 95%) [%]	0.09	0.06

Project_Payback

Table B.3. Representative statistics from the *Project_Payback* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

	Probability Distribution	
Statistics – Project_Payback [years]	**Uniform**	**Triangular**
Mean [years]	22.13	21.81

Typical error [years]	0.06	0.05
Median [years]	25.00	25.00
Mode [years]	25.00	25.00
Standard Deviation [years]	5.56	5.20
Variance [years^2]	30.96	27.02
Kurtosis	0.89	0.05
Asymmetry	-1.60	-1.27
Range [years]	19.20	18.69
Minimum [years]	5.80	6.31
Maximum [years]	25.00	25.00
Sample Total number	10,000	10,000
Loss probability [%]	-	-
Confidence interval (acceptance level 95%) [years]	0.11	0.10

Project_LCOE

Table B.4. Representative statistics from the *Project_LCOE* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

	Probability Distribution	
Statistics – Project_LCOE [€/MWh]	**Uniform**	**Triangular**
Mean [€/MWh]	338.57	297.50
Typical error [€/MWh]	1.43	0.90
Median [€/MWh]	309.70	283.35
Mode [€/MWh]	-	222.82
Standard Deviation [€/MWh]	142.60	90.00
Variance [(€/MWh)^2]	20,335.67	8,100.56

Kurtosis	1.39	1.23
Asymmetry	1.09	0.91
Range [€/MWh]	1,004.32	740.22
Minimum [€/MWh]	94.67	106.80
Maximum [€/MWh]	1,098.99	847.01
Sample Total number	10,000	10,000
Loss probability [%]	-	-
Confidence interval (acceptance level 95%) [€/MWh]	2.80	1.76

Figure list

Figure 1. Conceptual scheme of the income statement model for the economic valuation of Spanish CSP assets under the RD 413/2014 framework. Source: self-elaboration based on [2].

Figure 2. Conceptual comparison schema between the deterministic and the probabilistic analysis of the Spanish CSP system under the RD 413/2014 framework. Source: self-elaboration.

Figure 3. Methodology for the application of the DCF-MC analysis in the RD 413/2014 economic model. Source: self-elaboration.

Figure 4. Characterization of the SCSPS: (a) classification according to the total number of facilities, (b) classification according to the total installed capacity. Source: self-elaboration.

Figure 5a. Sensitivity analysis results. Impact of the parameters variation on the *Project_NPV*. Source: self-elaboration.

Table list

Table B.2. Representative statistics from the *Project_IRR* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

Table B.3. Representative statistics from the *Project_Payback* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

Table B.4. Representative statistics from the *Project_LCOE* MC simulation with uniform and triangular PDFs. Source: self-elaboration.

Table 1. Values of the regulatory parameters for a CSP type facility IT-00609. Source: self-elaboration based on [54-56].

Code	***a***	***VU*** ***[years]***	***VI_a*** ***[€/MW]***	***$C_{1.a}$***	***$Rinv_{2013}$*** **[€/MW]**	***$Rinv_{2014\text{-}2016}$*** **[€/MW]**	***$Rinv_{2017\text{-}2019}$*** **[€/MW]**	***$Nh\_max_{(Ro)2013}$*** **[h]**	***$Nh\_max_{(Ro)2014\text{-}2016}$*** **[h]**	***$Nh\_max_{(Ro)2017\text{-}2019}$*** **[h]**	***Nh_min_{2013}*** **[h]**	***$Nh\_min_{2014\text{-}2016}$*** **[h]**	***$Nh\_min_{2017\text{-}2019}$*** **[h]**	***Uf_{2013}*** **[h]**	***$Uf_{2014\text{-}2016}$*** **[h]**	***$Uf_{2017\text{-}2019}$*** **[h]**
IT-00609	2011	25	6,184,027	1	261,271	557,683	559,440	1,274	2,720	2,704	326	1,632	1,622	190	952	946

Year	***Pm_e_i*** **[€/MWh]**	***$C\_Eexp\_e_i$*** **[€/MWh]**	***Pmf_i*** **[€/MWh]**	***C_Eexpf_i*** **[€/MWh]**	***Nh_e_i*** **[h]**	***$Nh_{i,j}$*** **[h]**	***$LS2_{i,j}$*** **[€/MWh]**	***$LS1_{i,j}$*** **[€/MWh]**	***$LI1_{i,j}$*** **[€/MWh]**	***$LI2_{i,j}$*** **[€/MWh]**	***Ro_i*** **[€/MWh]**
2011	–	–	–	–	–	–	–	–	–	–	–
2012	299.30	85.34	–	–	2,449	–	–	–	–	–	–
2013	302.46	105.67	52.35	89.09	1,172	1,274	–	–	–	–	36.742
2014	–	–	49.21	87.21	–	2,720	56.21	52.21	44.21	40.21	38.003
2015	–	–	50.55	87.96	–	2,715	57.52	53.52	45.52	41.52	37.418
2016	–	–	50.78	88.83	–	2,709	57.75	53.75	45.75	41.75	38.055
2017	–	–	44.96	89.74	–	2,704	49.81	46.33	39.35	35.87	44.777
2018	–	–	43.60	90.60	–	2,698	48.30	44.92	38.16	34.78	47.006
2019	–	–	43.94	91.48	–	2,693	48.68	45.28	38.46	35.06	47.533
2020	–	–	54.57	92.36	–	2,688	60	56	48	44	–