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METHODOLOGY FOR OBTAINING SIMPLIFIED MODELS FOR THE LONG-TERM ENERGY MANAGEMENT OF RENEWABLE ASSETS UNDER A HIGH DEGREE OF UNCERTAINTY

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Abstract

This paper addresses the attainment of a methodology aimed at obtaining simplified models embedding the regulatory constraints imposed by the country-specific remuneration mechanisms in the energy management system of long operating life renewable assets under a high degree of uncertainty. This methodology, composed of different steps in which sensitivity analysis as well as Monte Carlo simulation play a key role, is focused on a significant case study that has implemented two of the most widely used worldwide remuneration mechanisms in the promotion of renewable energies, i.e., feed-in tariffs and auctions. The earnings before interest, tax, depreciation and amortisation have been used as the output variable of the energy management model, as it is essential to take into account both revenues and operating costs of these renewable assets to manage them optimally. Some valid simplified models have been achieved by applying the proposed methodology to the case study with generalized errors below 5%. Specifically, one simplified energy management system model has been obtained under the feed-in tariff scheme, which involves acting on almost 40% of the equations of the original model and reducing the initial input parameters by 22%. Meanwhile, two simplified energy management system models have been obtained under the auction scheme. The most conservative simplified model involves acting on almost 50% of the equations of the original model and reducing the initial input parameters by 35%, while in the less conservative case it involves acting on more than 50% of the equations of the original model and reducing the initial input parameters by 42%. In short, although the uncertainty on the energy assets cannot be completely eliminated, it can be considerably reduced by facilitating the assessment of its prospective financial results. The validity of the achieved simplified models demonstrates the suitability and usefulness of the proposed simplifying methodology, providing a touch of quality in the long-term judgement and decision-making of the stakeholders when optimally managing renewable energy facilities under any type of remuneration scheme.

Keywords

Energy management, Renewable energy, Simplifying methodology, EBITDA approach, Support policies, Uncertainty

1. Introduction

1.1. Setting the context

Global warming has become a deep concern of this century, and the worldwide energy sector is not an exception on this extremely challenging field. In this regard, it is changing in promising ways with widespread adoption of renewables, which are the backbone of the fundamental energy sector decarbonisation (IRENA, 2020).

Much of the progress in deploying renewable energy (RE) technologies has been acquired due to country-specific government policies and regulatory frameworks, coupled with ambitious goals (Liu et al., 2019; REN21, 2020). It is important to note that, by the end of 2019, most of the countries worldwide had RE support policies in force. In this respect, the most common policy mechanisms are feed-in policies, auctions, renewable portfolio standards (RPS) and other quota obligations along with tradable green certificates (TGC), as well as financial incentives, although to a lesser extent (REN21, 2020).

In 2019, RE continued to increase their cost-competitiveness worldwide, therefore being highly demanded more sophisticated support policies able to address other objectives beyond the traditional ones. Accordingly, auctions continued to gain ground from feed-in policies as incentive schemes (IRENA et al., 2018; REN21, 2020). Nowadays, these mechanisms are the most commonly used worldwide to foster RE. Feed-in policies were in place in 113 regions by the end of 2019, while the total number of countries that have used competitive auctions increased to 109 (REN21, 2020). On one side, feed-in pricing mechanisms, namely feed-in tariffs (FITs) and feed-in premiums, have been paramount in encouraging RE projects worldwide, since they have provided a stable income throughout the useful life of facilities, improving their profitability. Nevertheless, their main challenge is to set, maintain and adjust the tariff or premium rate at the appropriate level as needed at any time. On the other side, auctions have gained popularity in recent years, owing to their design flexibility depending on the country-specific context and goals, as well as their potential for real price discovery. Besides, auctions try to reflect the degree of competition that already exists in a market, although they can lead to underbidding or limit the entry of small or new players in the market (IRENA et al., 2018).

1.2. State of the art

The exiting literature aimed at assessing RE support policies is quite extensive and it has grown considerably since the last decade, as evidenced in Shen et al. (2020). In this context, quite references can be highlighted dealing with the effectiveness of RE promotion policies in different countries worldwide and time periods. In particular, Liu et al. (2019) developed a fixed effect model combining both aggregate and specific RE policies in the same analysis framework to evaluate the impact of these promotion policies using a panel dataset of 29 countries during the period 2000–2015. Likewise, Bersalli et al. (2020) proposed an econometric analysis to assess the effectiveness of different RE policies based on a panel data of 20 Latin American and 30 European countries during the period 1995–2015, while Romano et al. (2017) analysed the effectiveness of green policies focusing on a panel of 56 developed and developing countries during the period 2004–2013. In turn, Andor and Voss (2016) derived optimal subsidy policies for RE technologies so as to assess the efficiency of popular promotion schemes, also assessing how the source of externalities should shape promotion. Meanwhile, Haas et al. (2011b) compared the theoretical and practical perspectives of quota-based certificate trading systems for an efficient and effective increase of electricity from renewable energy sources (RES) with other instruments like FIT, while Marques et al. (2019) assessed the nature of both the short and long-run effects of energy policies on both the installed capacity and the electricity generated by renewables technologies using a panel data of 46 world countries over the period 1996–2017. Moreover, Pitelis et al. (2020) assessed the effectiveness of different types of RE policies in fostering innovation activity in the Organisation for Economic Cooperation and Development electricity sector over the period 1990–2014. Other studies overview the support policies used to foster renewable electricity generation in energy transition processes, within the European electricity market (Haas et al., 2011a), in Algeria also analysing the present and future potential of RE technologies as well as the problem related to the use of RES and their promotion policies (Stambouli, 2011), in Lithuania in compliance with the European Union (EU) strategy and policy (Gaigalis et al., 2014), in several countries but focusing especially on their relevance and compatibility with the Brazilian renewable energy market (Aquila et al., 2017), across five federal countries in the Americas, i.e., Argentina, Brazil, Canada, Mexico and the United States of America, during the period 1998–2015 (Pischke et al., 2019), or based on a comparative mapping of 34 African country-specific RE policies (Müller et al., 2020). Conversely, some references can be found addressing policy dismantling processes in the RE sector, such as Gürtler et al. (2019), which is focused on the Spanish and Czech cases.

There is also a wide range of publications specifically addressing the analysis of feed-in policies and auctions. On the one hand, some works assess the effectiveness and impact of FIT policies in the deployment of RES, in Kenya (Ndiritu and Engola, 2020), focusing on the Chinese wind and solar power industry (Du and Takeuchi, 2020), focusing on the European wind and solar photovoltaic (PV) energy investments over the period 1992–2015 (Alolo et al., 2020), or focusing on the German household disposable incomes during the period 2010–2017 (Winter and Schlesewsky, 2019). In turn, the impact of RES on the Spanish electricity market under a FIT scheme is assessed in Gallego-Castillo and Victoria (2015), particularly exploring the balance between extra costs associated to FITs and savings due to the merit-order effect, while the impact of clean development mechanism on Korea's RE projects in conjunction with FIT subsidies is investigated in Koo (2017), through comparative investment analyses. Similarly, the FIT policy structure and its effect on the RES growth trend in the long-term is evaluated in Mousavian et al. (2020), through a system dynamics approach by using Iran as a case study. Further, the German FIT scheme for RE promotion is assessed focusing on its impact on innovation in Böhringer et al. (2017) by applying fixed effect negative binomial and Poisson panel data regression models. Meanwhile, other studies analyse the design and characteristics of FIT remuneration models for electricity generated from RES, in Victoria (Australia) by means of concept analysis techniques and mapping software (Martin and Rice, 2017), in two European countries, i.e., Germany and Spain (García-Alvarez and Mariz-Pérez, 2012), under market and regulatory uncertainty by using the real options framework (Barbosa et al., 2020), or focusing on market-independent fixed FITs under regulatory uncertainty (Ritzenhofen and Spinler, 2016). Likewise, a case study of Ontario's (Canada) FIT policies between 1997 and 2012 analysing how the political process affects RE policy design and implementation is presented in Stokes (2013). Furthermore, a low-risk FIT design to benchmark the existing Latin America and Caribbean region FITs is presented in Jacobs et al. (2013), while the worldwide FIT rates of marine RE are reviewed to suggest appropriate FIT values for this technology based on the net present value (NPV) approach in Malaysia in Lim et al. (2015). In turn, RE FIT models in different selected countries in Europe, United States, Australia, Asia and Africa are analysed with the aim of drawing lessons for Saudi Arabia in Ramli and Twaha (2015). Further, a significant number of papers compare the performance of FIT schemes with quota-based models such as RPS and TGC for RES, in the Spanish electricity system for the period 2008–2013 (Ciarreta et al., 2017), focusing on the substitution effect of RPS and TGC for FIT by using a multi-region power market model and, particularly, China as a case study (Zhang et al., 2018), examining how these renewable support policies affect the price and output levels of electricity in the Japanese monopoly market (Dong and Shimada, 2017), discussing by means of the levelized cost of electricity calculation whether RES, and specifically wind onshore and solar PV, under these support schemes can realize grid parity in China (Xin-gang et al., 2020), looking at the adoption of these RE policies at the national government level as a consequence of diffusion (Alizada, 2018), focusing on onshore wind power in the EU-28 over the period 2000–2014 (García-Álvarez et al., 2017), or by using a dynamic long-term capacity investment model to analyse the impact of these mechanisms in terms of affordability, reliability and sustainability of electricity supply on power markets (Ritzenhofen et al., 2016). Similarly, the economic efficiency of FIT and RPS schemes, by conducting cost-benefit analysis and calculating NPV, is comparatively assessed in the South Korean RE market in Choi et al. (2018), while the different effects of FIT and RPS, in terms of research and development input, quantity of energy, market price, consumer surplus and social welfare are compared in Sun and Nie (2015). Further, the windfall profits generated through FIT and RPS policies are explored and compared for the case of South Korea in Kwon (2015), while models of long-term development of the RE power industry in China under FIT and RPS schemes are established by using system dynamics in Yu-zhuo et al. (2017). Meanwhile, some studies compare the feasibility of FIT with auction schemes for promoting renewable electricity generation, in the Gulf Cooperation Council states (Atalay et al., 2017), where there is an ongoing effort to diversify the energy mix towards more RES, or in Germany explaining from an historical institutionalist perspective the shift from FITs towards auctions (Leiren and Reimer, 2018).

On the other hand, other works discuss the effectiveness of auction support schemes in the promotion of power generation from RES, on a global basis during the period 1990–2017 (Matthäus, 2020), across the world and specifically presenting the case of Cyprus for allocating 50 MW of PV projects (Kylili and Fokaides, 2015), in Turkey (Yalılı et al., 2020), in various developing countries from South Africa, Brazil, India and China (Hansen et al., 2020), or in Brazil, France, Italy, the Netherlands and South Africa (Winkler et al., 2018). Similarly, the auction design features needed to achieve India's renewable targets are suggested in Shrimali et al. (2016), by means of assessing the effectiveness and feasibility of 20 RE auctions around the world in terms of cost-effectiveness, deployment effectiveness and equity in project allocation. In turn, other papers analyse the design, characteristics and impact of auction remuneration models for energy produced from RES. Specifically, a combinatorial auction design that allows to implement regional target capacities, provides a simple pricing rule and maintains a high level of competition between bidders by permitting package bids is proposed in Bichler et al. (2020), while the influence of RE auction design features on auction outcomes and technology diversity is assessed in Haelg (2020). Further, the design elements and functioning of the stand-alone solar home systems auction in Peru is analysed in Lucas et al. (2020), while the India's 2017–2018 e-reverse auctions for allocating RE capacity is evaluated in Bose and Sarkar (2019). Likewise, a bridge between auction theory and the implementation of auctions in the context of RE support is developed in Haufe and Ehrhart (2018), while different criteria for the design of multi-unit RE auctions in small markets are investigated in Welisch (2019), by using the Danish multi-technology renewable auction as a case study. Moreover, the Turkey's solar PV auction is analysed and compared with Brazilian and South African renewable support auction designs in Sirin and Sevindik (2021), while auctions for RES as a means of contributing to the fulfilment of RE targets are designed in Kreiss et al. (2017). Similarly, the wind onshore renewable auctions in Germany are assessed by using an agent-based modelling approach in Anatolitis and Welisch (2017), while the impact of the design of the German wind power auctions held in 2017 on actor diversity, bidding behaviour and the risk of winning projects not being realized is examined in Lundberg (2019). In addition, reverse auction market design for decentralised off-grid solar PV deployment as a potential solution for the Nigeria power sector is proposed in Arowolo (2019), while the advantages and drawbacks of different design elements for renewable electricity auctions worldwide according to different assessment criteria are analysed in del Río (2017). Likewise, auctions for the allocation of offshore wind contracts for difference in the United Kingdom from both a qualitative and a quantitative approach are analysed in Welisch and Poudineh (2020), while South Korea's RPS policy is examined by focusing on the regulation of technology competition under the RPS scheme and on market risk mitigation in Kwon (2018). In turn, the impact of the policy-induced uncertainty and auction design on the cost of capital of RE power plants in Europe is assessed in Botta (2019), while the recent tendency in auctions of low record RE bid prices are analysed by using data from several countries, technologies and remuneration designs in Martín et al. (2020). Moreover, a modelling approach to determine competitive and risk-adequate RE auction bids, to ensure that the investment requirements of both equity and debt investors are met, is presented and then tested in the German onshore wind projects in Stetter et al. (2020).

1.3. Justification and main contributions of the article

In spite of the extensive state of the art dealing with the different remuneration mechanisms for the promotion of RES, these mechanisms are not usually taken into account for the determination of the optimal energy management strategy of RE assets. The lack of inclusion of the regulatory constraints could result in a suboptimal energy management strategy, as demonstrated in both de la Hoz et al. (2019) and de la Hoz et al. (2020). In order to optimise the available resources, as well as the profitability of electricity generation, it is critical to embed into the energy management system (EMS) model the regulatory constraints imposed by the remuneration mechanisms.

One of the main reasons behind this lack of inclusion of the regulatory framework inside the EMS models might be the lack of specialized knowledge on the country-specific regulations. This could lead to skip modelling the regulatory constraints on the belief that they are not relevant for the model outcome and therefore continuing with the traditional approach that simply relies on the minimization of a cost function. Another reason for ignoring the regulatory reality could be the frequently complex, uncertain and fast changing framework that hinders to keep updated with the rules governing these RE assets.

Conversely, including the regulatory framework in the EMS models usually results in a significant increase of complexity that difficult to assess the impact of these added constraints in the model outcome, which might veil the energy management strategy.

In order to help solving an actual problem and contribute to the future decision-making of RE stakeholders, this work addresses the attainment of a methodology aimed at obtaining simplified models embedding the regulatory constraints in the EMS of long operating life renewable assets, which has not yet been dealt with so far. Up to the authors' knowledge, this paper is the first to facilitate the operating decision-making and management of RE assets by proposing a methodology for the simplification of their physical model, taking into account the economic and regulatory constraints set by the country-specific support policies. In this regard, this paper is aimed to fill this gap in the scientific literature.

The general methodology here presented is intended to be a useful tool providing a touch of quality in the judgement and decision-making of the stakeholders when managing RE assets. Thus, allowing the managers a better qualitative understanding of the system as well as the identification of both accessory parameters and those especially relevant in the asset management. Furthermore, this methodology aims to be transferable to any type of remuneration scheme for the promotion of RE power plants worldwide. In this regard, this study has focused its attention on the two most extended remuneration mechanisms, namely, FITs and auctions.

The paper is organised as follows. After contextualising the subject matter analysed in this contribution by reviewing the existing state of the art, identifying the gap in the literature and highlighting the added value provided by the study, a step-by-step description of the methodology for obtaining simplified models for the EMS of RE facilities is conducted in Section 2. Subsequently, the simplification methodology is checked by means of the analysis of FIT and auction schemes for the case study in Sections 3–8. Specifically, Section 3 defines the assessed case study, Section 4 describes the RE plant EMS models considering the economic and regulatory constraints, Section 5 attains the simplified EMS model proposals for each remuneration scheme under the case study by applying the sensitivity analysis method, while Section 6 validates them by using the Monte Carlo (MC) simulation and Section 7 presents the optimal energy management long term strategy. Thereupon, Section 8 presents the discussion of results and the final remarks. To sum up, all noteworthy factors are properly systematised and conclusions are drawn in Section 9.

2. Methodology

The methodology here presented for the simplification of the EMS model for renewable assets is addressed in five different steps, as depicted in Fig. 1. In the subsequent subsections, each of the steps of this simplifying methodology is described in detail.

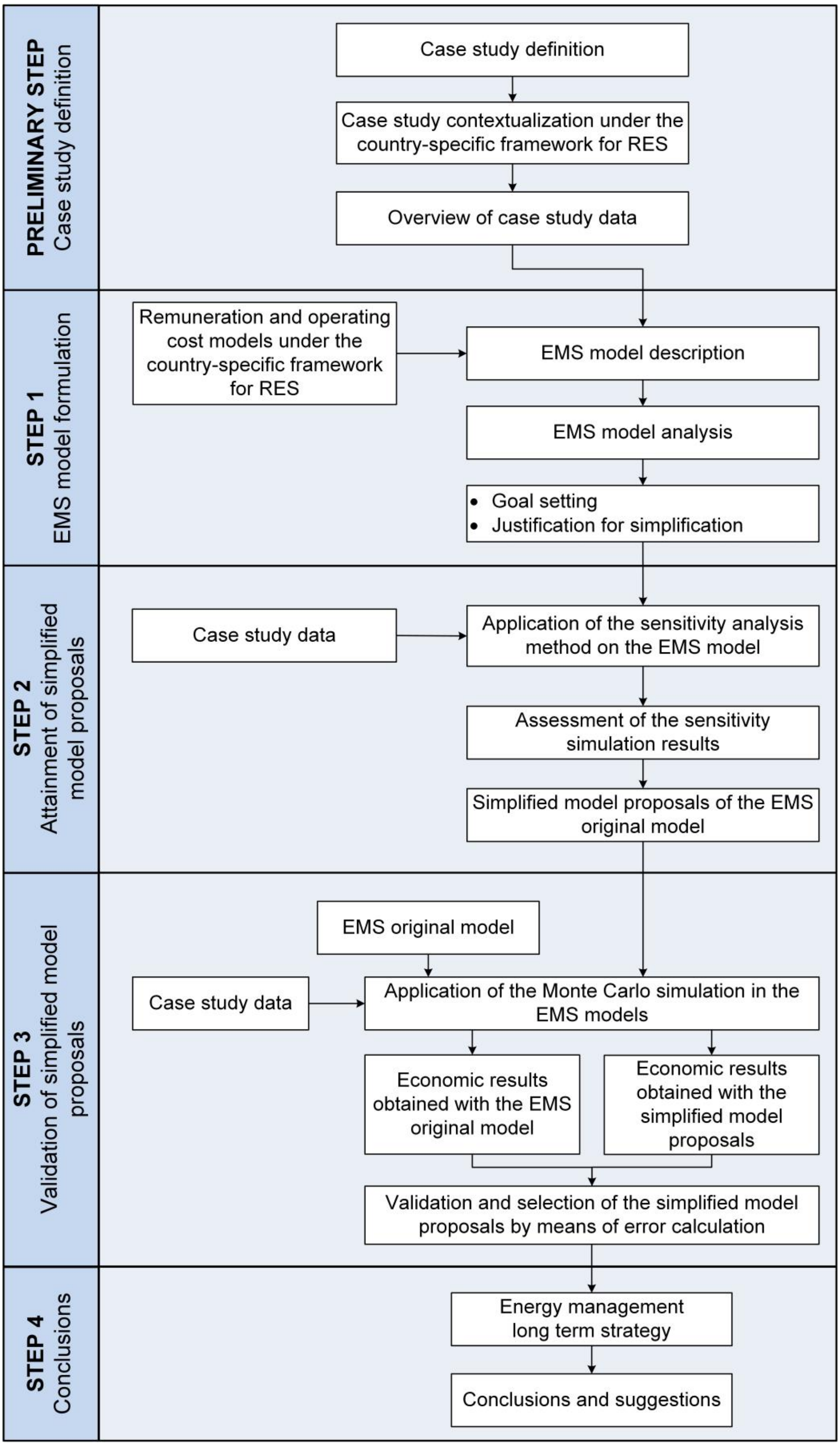
PRELIMINARY STEP
Case study definition
Case study definition
Case study contextualization under the country-specific framework for RES
Overview of case study data
STEP 1
EMS model formulation
Remuneration and operating cost models under the country-specific framework for RES
EMS model description
EMS model analysis
• Goal setting
• Justification for simplification
STEP 2
Attainment of simplified model proposals
Case study data
Application of the sensitivity analysis method on the EMS model
Assessment of the sensitivity simulation results
Simplified model proposals of the EMS original model
STEP 3
Validation of simplified model proposals
EMS original model
Case study data
Application of the Monte Carlo simulation in the EMS models
Economic results obtained with the EMS original model
Economic results obtained with the simplified model proposals
Validation and selection of the simplified model proposals by means of error calculation
STEP 4
Conclusions
Energy management long term strategy
Conclusions and suggestions

Fig. 1. Methodology for the simplification of the EMS for RE plants under a regulatory and economic scheme. Source: self-elaboration.

2.1. Preliminary step: Case study definition

As depicted in Fig. 1, the simplification analysis requires a preliminary step where all the essential data of the case study are collected. Thus, the technology type of the renewable power plant, its location and its main technical features must be first characterised, as observed in Fig. 2. Subsequently, the case study is contextualised according to the country-specific regulatory framework for RES, extracting the corresponding economic and regulatory constraints as well as the remuneration and operating cost schemes.

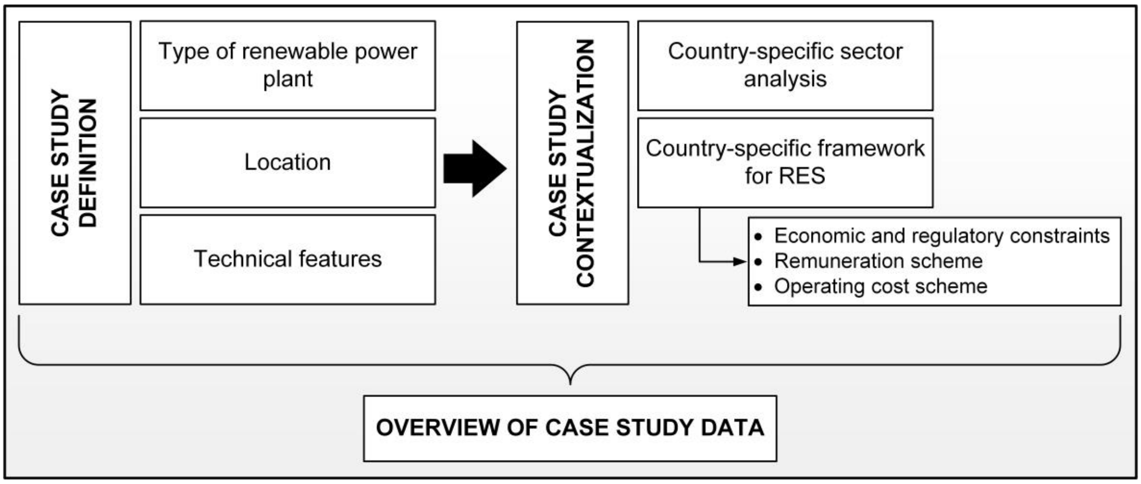

Fig. 2. Details of the case study definition. Source: self-elaboration.

2.2. Step 1: EMS model formulation

As can be observed in Fig. 1, the aim of Step 1 is to obtain the EMS model of the RE plant, which must be able to depict in detail its behaviour in the physical, economic and regulatory fields. In this regard, one of the most common metrics employed for the evaluation of the economic performance of a power plant is the earnings before interest, tax, depreciation and amortisation (EBITDA).

The merit of the EBITDA relies on focusing directly in the operating performance of the plant, skipping the effect of financial, accounting and tax decisions. Besides, the use of EBITDA, which includes the revenues, is better than other approaches that only consider the operating costs when analysing the operation of the asset. In this vein, the inclusion of the revenues facilitates the modelling of regulatory constraints, as revenues are subjected to the regulatory framework of the power sector.

Fig. 3 illustrates the relationship between the different input parameters of a power plant (i.e., technological, physical, economic and regulatory) and the EBITDA.

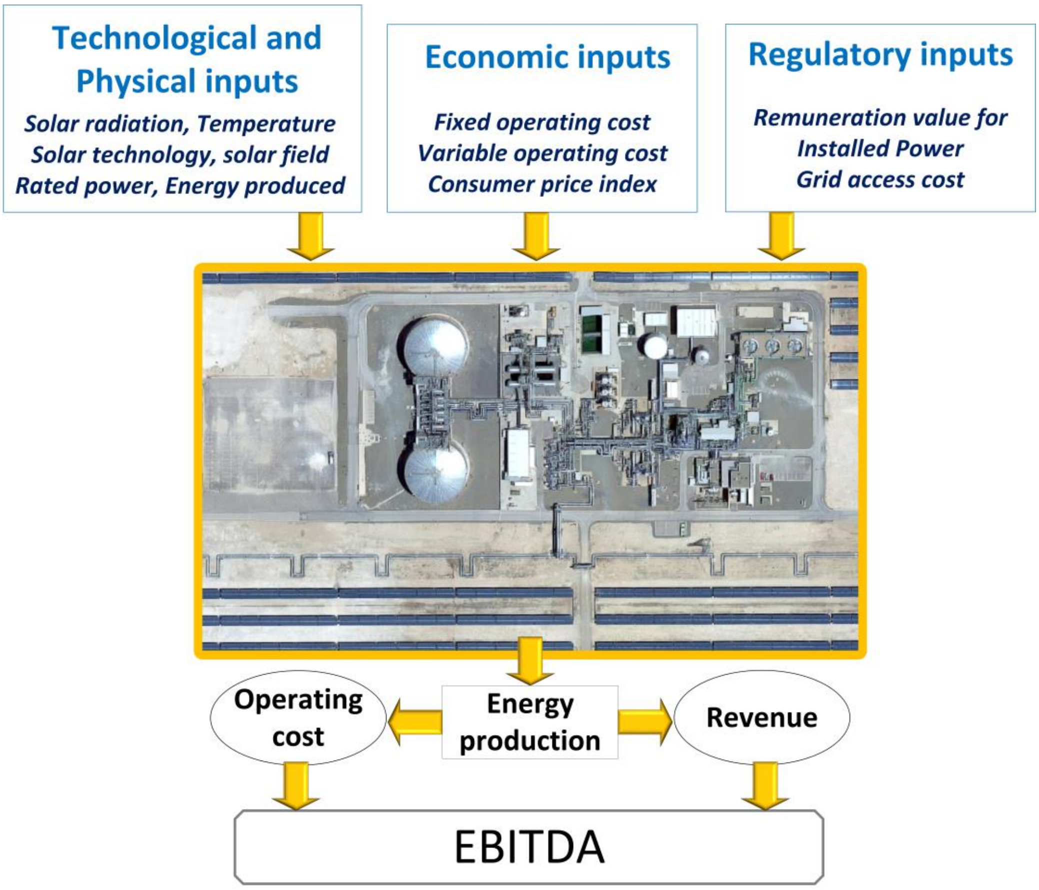

Fig. 3. Operating profitability approach for the EMS model formulation. Source: self-elaboration.

In the year *i*, the $EBITDA\_{i}$ is determined as the difference between the income from operating the energy asset ($Revenue\_{i}$) and the total operating cost for running this facility ($Operating\_Cost\_{i}$):

$$EBITDA\_{i} = Revenue\_{i} - Operating\_Cost\_{i} \quad (1)$$

The resulting EMS model obtained in Step 1 will provide the inner relations between the revenue and the cost and the produced energy. This model in some cases might be complex, and therefore it should be advisable to undertake its simplification, which is that will be done in the Step 2 of this methodology.

It must be noticed that despite the output variable of the EMS model is the $EBITDA\_{i}$, in order to evaluate the economic performance of the asset throughout its life time, the total EBITDA has to be computed as follows:

$$EBITDA = \sum_{i} \frac{EBITDA_{-i}}{(1 + t_{-ur})^{i}} \quad (2)$$

Where $t_{\_ur}$ is an update rate that takes into account the time effect on the value of money.

2.3. Step 2: Attainment of simplified model proposals

Step 2 intends to determine the first proposals of simplified EMS models through the application of the sensitivity analysis technique, as seen in Fig. 1. In this respect, Fig. 4 provides a detailed conceptual scheme with the methodology for conducting the sensitivity analysis simulation in the EMS model.

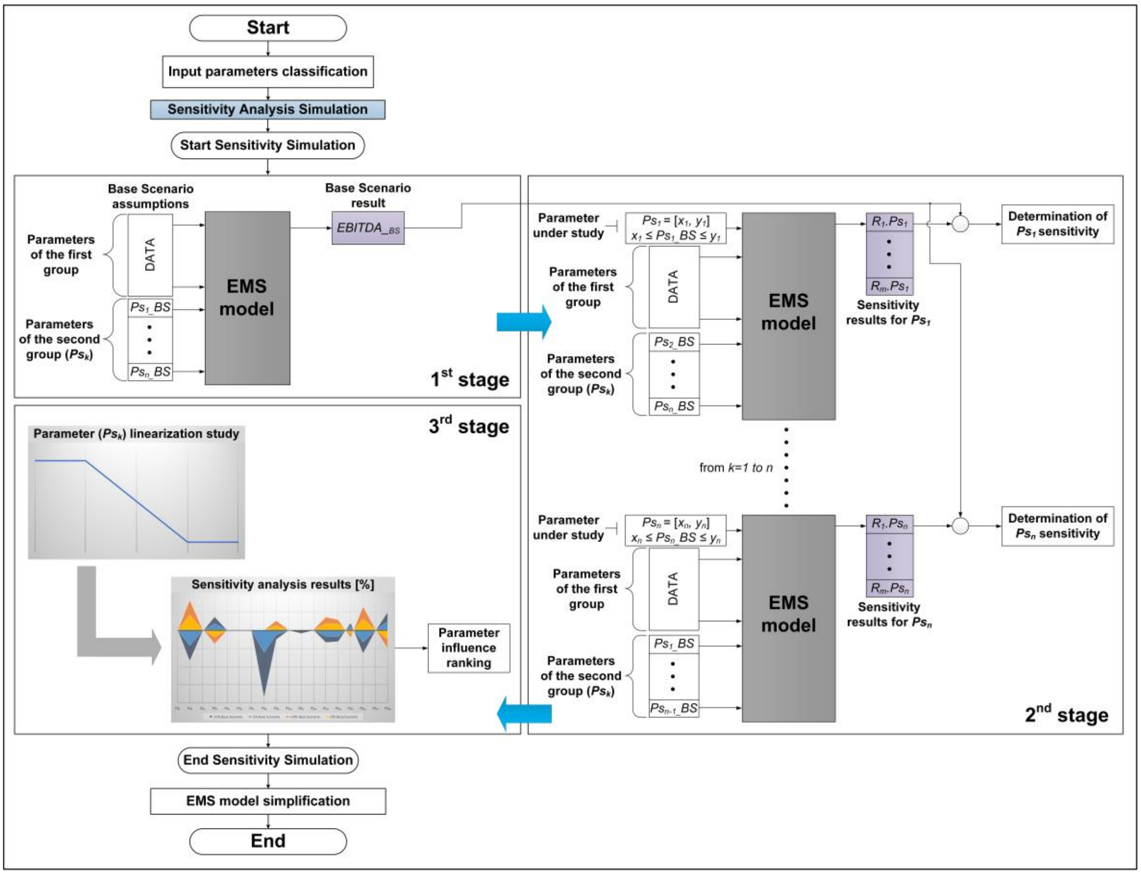

Fig. 4. Details of the methodology for the attainment of simplified model proposals. Source: self-elaboration.

As observed in Fig. 4, before proceeding with the sensitivity analysis simulation, it is necessary to classify all the input parameters of the EMS model into two different groups. On the one hand, the first group called "DATA" comprises those parameters whose value is known and constant throughout the analysis period. On the other hand, the second group contains those parameters showing uncertainty and variability either because of the physical, economic and regulatory uncertainty or because of the reticence of the country-specific RE sector to provide certain data.

Then, the first stage of this process consists of determining the base scenario result ($EBITDA_{\_BS}$) for the *EBITDA*, as illustrated in Fig. 4. The $EBITDA_{\_BS}$ acts as a reference against which the sensitivity analysis results can be compared to determine the influence of each of the input parameters of the second group in the EMS model outputs.

Subsequently, in the second stage it is analysed how sensitive the EMS model is to individual variations of each of the *n* input parameters (Ps_k) of the second group, as seen in Fig. 4. For this purpose, for each Ps_k it is defined an interval bounded by a lower limit (x_k) and an upper limit (y_k) set at -10% and +10%, respectively, of the base scenario value (Ps_{k_BS}), with a discretization step of 5%. Then, the EMS model is simulated by varying a single input parameter Ps_k in each of the sensitivity analyses, while the rest of the parameters remain constant at the values set in the base scenario. Thereupon, the sensitivity analysis results of each parameter Ps_k for the *EBITDA* are compared to the $EBITDA_{\_BS}$ reference value, obtaining the individual impact of each of the *n* second group parameters on the output variable of the EMS model.

Finally, the obtained results are examined in the third stage, in order to perform the corresponding ranking of parameter influence on the *EBITDA* of the EMS model, as seen in Fig. 4. In this way, the parameters that most affect the *EBITDA* are identified, as well as those with the least impact and that can hence be neglected, resulting in one or several simplified model proposals.

2.4. Step 3: Validation of simplified model proposals

As shown in Fig. 1, the MC simulation of the case study is executed in each of the EMS models, i.e., the original EMS and the simplified model proposals, in Step 3. Thereafter, the economic results obtained from the stochastic simulation of the simplified model proposals are compared with those attained under the original model, obtaining the corresponding errors. Then, those simplified model proposals satisfying the required accuracy levels can be accepted as valid.

From the above, it is clear that the key point of Step 3 is the implementation of the MC approach. Accordingly, a detailed diagram with the methodology applied to carry out the validation process of each of the simplified model proposals is provided in Fig. 5.

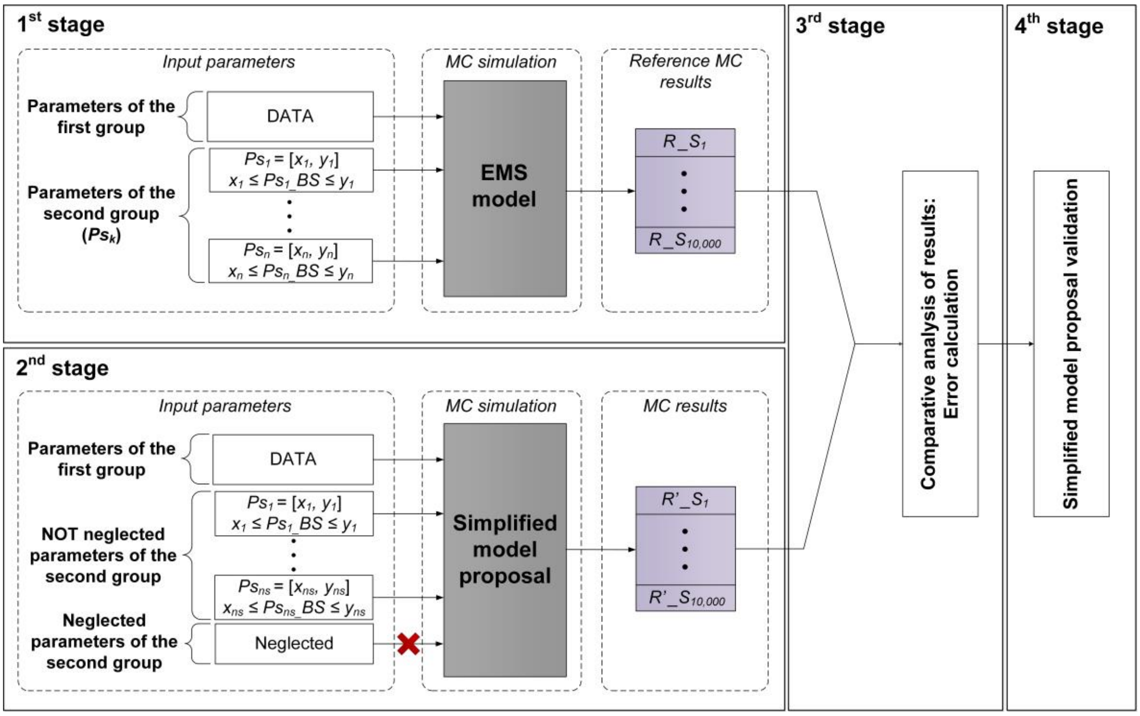

Fig. 5. Details of the methodology for the validation of simplified model proposals. Source: self-elaboration.

As seen in Fig. 5, the MC reference results for the *EBITDA* are obtained in the first stage for the original EMS model. This is done by randomly and simultaneously varying the *n* uncertain input parameters of the second group according to its probability density function (PDF), while the input parameters of the first group remain unchanged.

Specifically, a triangular PDF is contemplated for each of the *n* uncertain parameters. In this way, a certain judgement is incorporated to the MC simulation as a result of the authors' experience, indicating a higher probability of occurring of the base scenario value (mode) and assuming a linear decrease to zero of the probability of the rest of the interval values as we move away from the mode. A total of 10,000 samples are evaluated, ensuring the stabilization of the average value of the *EBITDA*.

Secondly, once the reference results for the *EBITDA* are obtained, the MC simulation process is repeated for each of the simplified model proposals, as depicted in Fig. 5. Since the number of input parameters of the simplified model proposals is lower than under the original EMS model, the MC simulation time of such simplified models is significantly smaller.

Then, as shown in Fig. 5, the third stage of the validation process consists of carrying out a comparative analysis between the *EBITDA* results of the simplified model proposals and those achieved under the original EMS model (Reference MC results), determining the corresponding errors.

Finally, in the fourth stage, each of the simplified model proposals are validated based on the error obtained in the third stage and those simplified models satisfying the required accuracy levels are selected, as seen in Fig. 5.

2.5. Step 4: Energy management long term strategy and conclusions

In Step 4, an energy management long term strategy is obtained using the simplified models and the sensitivity analysis. For each remuneration scheme, the use of the simplified models results in a simplified EBITDA expression, which leads to the most suitable operation strategy of the power plant. Lastly, a critical analysis of the validity of the proposed simplification methodology is carried out, employing the results obtained for the selected case study. Thus, the final remarks on the matter are presented, and conclusions and suggestions are raised, as shown in Fig. 1.

3. Case study definition

The selected RE asset corresponds to the concentrating solar thermal power (CSP) technology, which reached a global capacity of 6.2 GW in 2019 after experiencing a growth of 11% over the previous year. Moreover, at the end of 2019 about 1.1 GW of new plants were under construction around the world, which represents a future increase in current CSP capacity of roughly 20% (REN21, 2020). Accordingly, and as denoted in the previous work of the authors (de la Hoz et al., 2018), the research on CSP has gained much importance in the last decade, evincing the great momentum of the sector.

In this regard, Spain is the global leader country in cumulative CSP capacity with 2,304 MW (37.2% of the world total and assets exceeding 13,000 M€ (de la Hoz et al., 2018)), followed by the United States of America with 1,738 MW (REN21, 2020). Therefore, it has been deemed appropriate to select the Spanish CSP sector (SCSPS) as the case study. With the aim of selecting a representative CSP asset, it has been chosen a 50 MW facility of parabolic trough technology without thermal energy storage. This type of plant accounts for 28% of the total number of CSP plants (CSPP) in Spain and for 30% of the total installed capacity.

In addition, the Spanish case is especially relevant because the RE sector has undergone continuous regulatory changes since the adoption of the first Spanish electricity law in 1997, moving from simple FIT schemes to complex auctions mechanisms to promote RES. Spain has implemented both mechanisms and provides all the required information for their analysis, which is another merit for selecting this country as the case study. In addition, the most recently repealed FIT and auction mechanisms have been chosen for the analysis, as their already closed period of application allows taking the due perspective when applying them on the asset under study.

Specifically, the FIT scheme corresponds to Royal Decree (RD) 661/2007 and the auction mechanism to RD 413/2014. What makes this auction mechanism relevant is the introduction of remuneration for the undertaken investment granting a monetary amount per unit of installed power, in addition to the energy remuneration term.

As a working assumption, the regulatory parameter values of both frameworks are presented in Tables 1 and 2, respectively.

Table 1
Values of the regulatory parameters for a CSP facility under the FIT mechanism defined by RD 661/2007. Source: self-elaboration based on RD 661/2007 (2007).

Regulatory parameters	
FIT_{a} [c€/kWh]	26.9375
FIT_{a+25} [c€/kWh]	21.5498
Useful life [years]	25
r_{i}	25 basis points until 2012
	50 basis points from 2013

Table 2
Values of the regulatory parameters for a CSP asset under the auction mechanism defined by RD 413/2014. Source: self-elaboration based on Orden ETU/130/2017 (2017); Orden IET/1045/2014 (2014) and RD 413/2014 (2014).

Note: Table 2 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.

4. Describing the EMS model formulation result

Once the case study has been fully defined and characterised, the problem statement as well as the justification for simplifying the EMS models under the country-specific legal-economic framework for RES are undertaken in Step 1.

The EMS model for Spanish CSP assets under the two remuneration mechanisms, i.e., RD 661/2007 FIT scheme and RD 413/2014 auction scheme, are depicted by means of conceptual block diagrams in Figs. 6 and 7, respectively. Note that the input parameters are located in blue-coloured boxes at the left side of the block diagrams shown in Figs. 6 and 7. In addition, the uncertain input parameters are framed in red colour. In turn, the intermediate calculation variables are placed in white-coloured boxes, while the $EBITDA\_{i}$ output variable is located in a green-coloured box at the upper right corner of the conceptual schemes. Finally, the mathematical operators used in these conceptual diagrams, namely, the addition, the multiplication and the subtraction symbols, are colored purple, yellow and orange, respectively.

For clarity and conciseness, the extended description of the EMS models under both the FIT and auction schemes is depicted in Annexes A and B, respectively. In this section, these models are described conceptually, stressing the inner relations between the physical and legal-economic constraints.

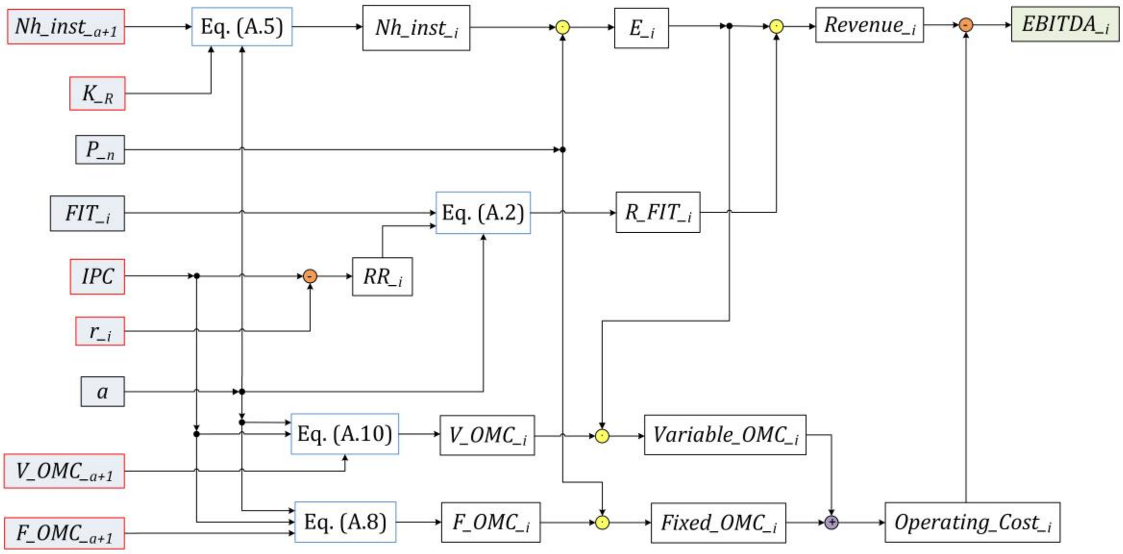

Fig. 6. Conceptual approach to the original EMS model under RD 661/2007 FIT scheme. Source: self-elaboration.

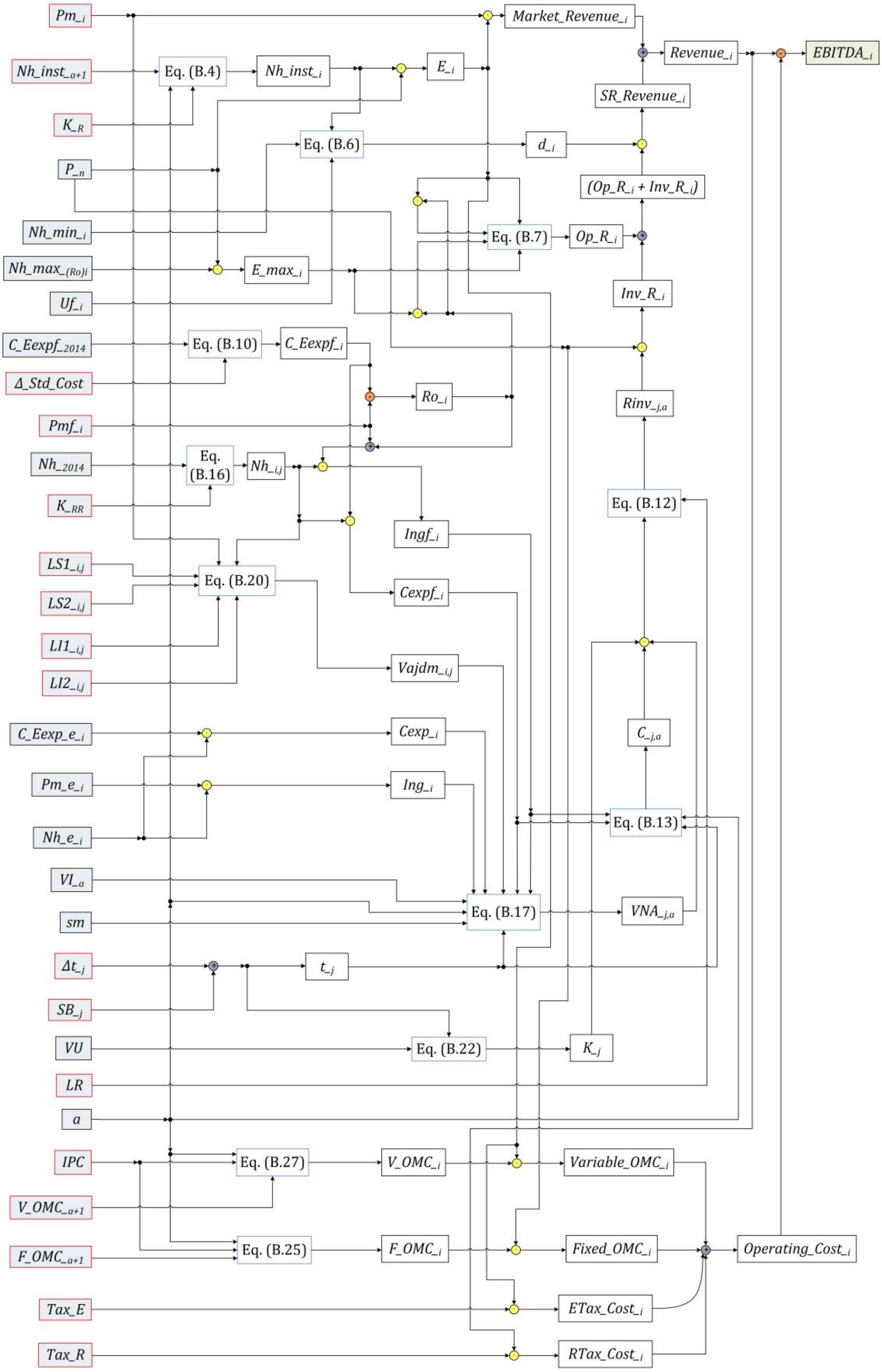
Pm_i
Market_Revenue_i
Nh_inst_a+1
Eq. (B.4)
Nh_inst_i
E_i
Revenue_i
EBITDA_i
SR_Revenue_i
K_R
Eq. (B.6)
d_i
P_n
(Op_R_i + Inv_R_i)
Nh_min_i
Eq. (B.7)
Op_R_i
Nh_max_(Ro)i
E_max_i
Uf_i
Inv_R_i
C_Eexpf_2014
Eq. (B.10)
C_Eexpf_i
Δ_Std_Cost
Ro_i
Rinv_j,a
Pmf_i
Nh_2014
Eq. (B.16)
Nh_i,j
Eq. (B.12)
K_RR
Ingf_i
LS1_i,j
Eq. (B.20)
Cexpf_i
LS2_i,j
LI1_i,j
Vajdm_i,j
LI2_i,j
C_j,a
C_Eexp_e_i
Cexp_i
Pm_e_i
Ing_i
Nh_e_i
Eq. (B.13)
VI_a
sm
Eq. (B.17)
VNA_j,a
Δt_j
t_j
SB_j
VU
Eq. (B.22)
K_j
LR
a
IPC
Eq. (B.27)
V_OMC_i
Variable_OMC_i
V_OMC_a+1
F_OMC_a+1
Eq. (B.25)
F_OMC_i
Fixed_OMC_i
Operating_Cost_i
Tax_E
ETax_Cost_i
Tax_R
RTax_Cost_i

Fig. 7. Conceptual approach to the original EMS model under RD 413/2014 auction mechanism. Source: self-elaboration.

For both EMS models the yearly operating cost (*Operating_Cost_$_i$*) is essentially the same, namely, the sum of the fixed (*Fixed_OMC_$_i$*) and variable (*Variable_OMC_$_i$*) operating and maintenance costs, as illustrated in Figs. 6 and 7. While the *Fixed_OMC_$_i$* is directly proportional to the CSPP nominal power (*P_$_n$*), the *Variable_OMC_$_i$* is proportional to the total energy produced (*E_$_i$*). In turn, *E_$_i$* depends on the CSPP *P_$_n$* and its annual number of equivalent operating hours (*Nh_inst_$_i$*)[1]. In both cases, these costs are annually updated according to the consumer price index (*IPC*).

The most significant differences rely on the yearly *Revenue_$_i$*. The CSPP remuneration model under RD 661/2007 FIT scheme is easily calculated as the product of the FIT remuneration (*R_FIT_$_i$*) by *E_$_i$*, as seen in Fig. 6. The *R_FIT_$_i$* is yearly updated according to the updating factor *RR_$_i$* obtained as the difference between the *IPC* and a curtailment rate defined by the Government (*r_$_i$*),

Nevertheless, the CSPP annual remuneration related to RD 413/2014 auction mechanism is quite the opposite. Although this remuneration scheme rewards energy production through the market revenue (*Market_Revenue_$_i$*) and the remuneration for the operation (*Op_R_$_i$*), the critical economic income is the remuneration for the investment (*Inv_R_$_i$*), as observed in Fig. 7.

The *Market_Revenue_$_i$* and the *Op_R_$_i$* are computed as *E_$_i$* multiplied by the annual average electricity market price per unit of produced energy (*Pm_$_i$*) and the annual remuneration for the operation per unit of produced energy (*Ro_$_i$*) regulatorily set, respectively. Conceptually, the *Inv_R_$_i$* might be considered a sort of stream of income derived from the cost of the investment and compound interest. However, the computation of the *Inv_R_$_i$* is not so simple and the complexity of the algebraic expressions and the high number of economic and regulatory parameters are shown in Fig. 7 and Annex B.

As derived from Annexes A and B (see Tables A.1 and A.2 and Tables B.1 and B.2, respectively) and Figs. 6 and 7, the modelling of the *EBITDA_$_i$* of a given CSPP under RD 661/2007 FIT scheme requires eleven equations, while under RD 413/2014 auction mechanism needs up to thirty equations, some of them of high intricacy. Furthermore, the EMS model under RD 661/2007 FIT mechanism requires a total of nine input parameters, presenting six of them, i.e., almost 70%, some degree of uncertainty (see the input parameters framed in red colour in Fig. 6). As for the EMS model under RD 413/2014 auction mechanism, eighteen of its thirty-one input parameters, i.e., almost 60%, introduce some degree of uncertainty in the model (see the input parameters framed in red colour in Fig. 7). Accordingly, the amount and typology of both the input parameters and the intermediate calculation variables increase the complexity of the EMS model.

In short, it is evident that the resulting models from a country-specific legal-economic framework may affect and hinder the energy management of RE facilities in the mid and the long term.

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[1] The CSPP *Nh_inst_$_i$* is defined as a decreasing function depending on the year when the CSP facility acquired the operating permit (*a*), its initial number of equivalent operating hours within the year *a+1* (*Nh_inst_$_{a+1}$*) and the yearly degradation rate (*K_$_R$*).

5. Sensitivity analysis for the attainment of simplified model proposals

As previously explained (see Section 2.3 along with Fig. 4), in Step 2 each of the EMS models under the analysed economic regimes are simulated for a base scenario, defined in the Tables 1 and 2, along with Table 3, to obtain its corresponding $EBITDA_{\_BS}$ reference value. The base scenario for RD 661/2007 FIT scheme and RD 413/2014 auction mechanism produces an $EBITDA_{\_BS}$ reference value of 631.59 M€ and 499,41 M€, respectively.

Thereupon, the impact of varying each of the uncertain input parameters on the output of the EMS models is analysed in comparison with their reference $EBITDA_{\_BS}$ to determine its sensitivity rate.

Table 3
Base scenario values for the uncertain input parameters under RD 661/2007 FIT scheme and RD 413/2014 auction mechanism. Source: self-elaboration.

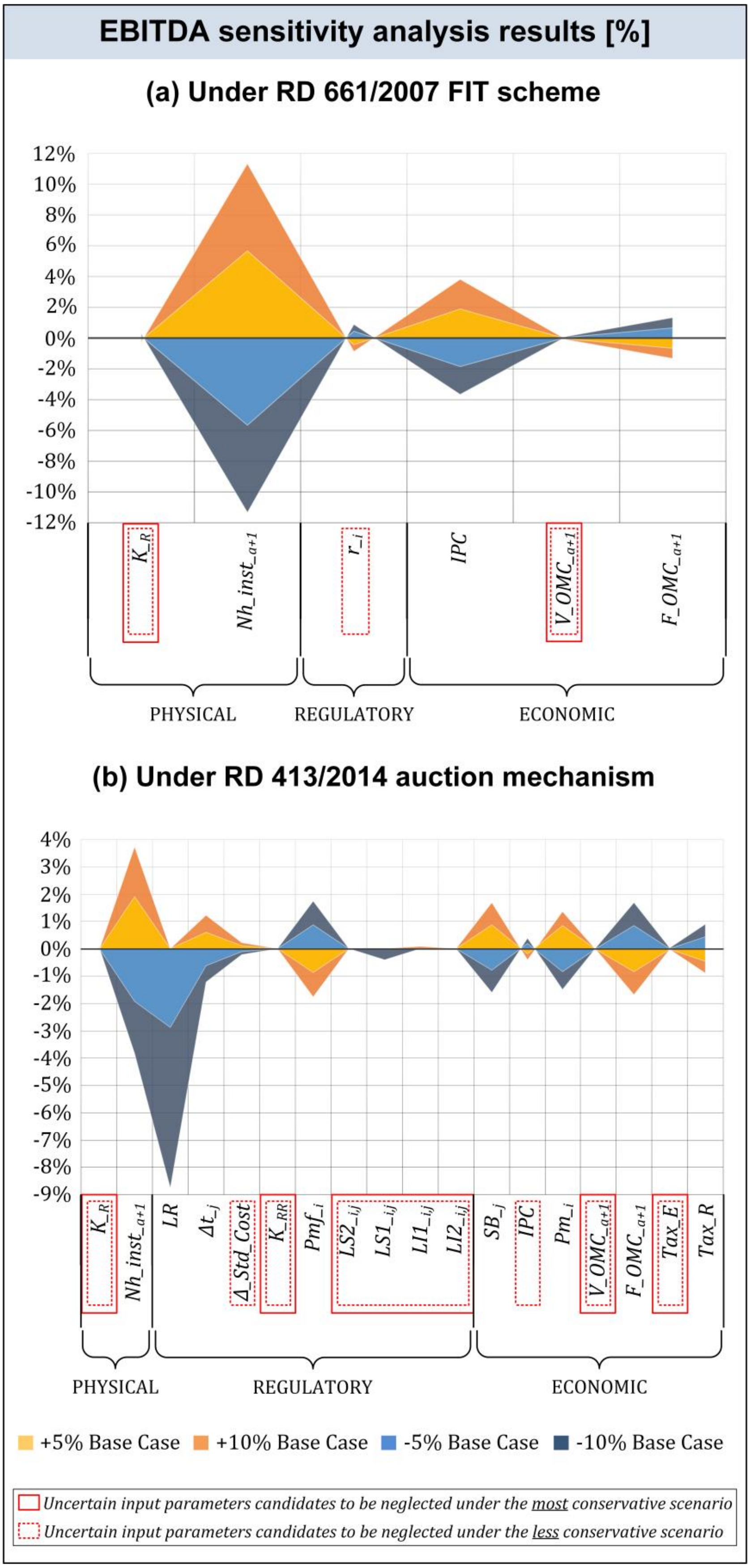
Parameters	**Base scenario values**	
	RD 661/2007 FIT scheme	**RD 413/2014 auction mechanism**
Physical parameters		
- Physical degradation rate ($K_{\_R}$)	0.2% (Orden IET/1045/2014, 2014)	0.2% (Orden IET/1045/2014, 2014)
- Initial equivalent operating hours ($Nh\_inst_{\_a+1}$)	1,873 h (Orden IET/1045/2014, 2014)	1,873 h (Orden IET/1045/2014, 2014)
Regulatory parameters		
- Curtailment for *IPC* ($r_{\_i}$)	0.25% (RD 661/2007, 2007)	-
- Reasonable profitability (*LR*)	-	7.398% (Orden IET/1045/2014, 2014)
- Differential added to $SB_{\_j}$ (Δt_j)	-	3% (Orden IET/1045/2014, 2014)
- Increment in standard operating cost (Δ_Std_Cost)	-	1% (Orden IET/1045/2014, 2014)
- Standard degradation rate ($K_{\_RR}$)	-	0.2% (Orden IET/1045/2014, 2014)

- Future estimated average market price (*Pmf_i*)	-	48.75 €/MWh (Orden ETU/130/2017, 2017; Orden IET/1045/2014, 2014)
- Second upper limit related to the deviations adjustment of *Pm_i* and *Pmf_i* (*LS2_i,j*)	-	54.04 €/MWh (Orden ETU/130/2017, 2017; Orden IET/1045/2014, 2014)
- First upper limit related to the deviations adjustment of *Pm_i* and *Pmf_i* (*LS1_i,j*)	-	50.29 €/MWh (Orden ETU/130/2017, 2017; Orden IET/1045/2014, 2014)
- First lower limit related to the deviations adjustment of *Pm_i* and *Pmf_i* (*LI1_i,j*)	-	42.78 €/MWh (Orden ETU/130/2017, 2017; Orden IET/1045/2014, 2014)
- Second lower limit related to the deviations adjustment of *Pm_i* and *Pmf_i* (*LI2_i,j*)	-	39.03 €/MWh (Orden ETU/130/2017, 2017; Orden IET/1045/2014, 2014)
Economic parameters		
- Average yield of the 10-year Spanish bonds (*SB_j*)	-	3.94% (INE, 2020)
- Consumer price index (*IPC*)	2.05% (INE, 2020)	2.05% (INE, 2020)
- Average electricity market price (*Pm_i*)	-	46.75 €/MWh (OMIE, 2020)
- Initial variable operating and maintenance cost (*V_OMC_a+1*)	2.57 €/MWh (IDAE, 2011; IRENA, 2012; Jordan and Kurtz, 2012)	2.57 €/MWh (IDAE, 2011; IRENA, 2012; Jordan and Kurtz, 2012)
- Initial fixed operating cost (*F_OMC_a+1*)	59.89 €/kW (IDAE, 2011; IRENA, 2012; Jordan and Kurtz, 2012)	59.89 €/kW (IDAE, 2011; IRENA, 2012; Jordan and Kurtz, 2012)
- Tax on the generated energy (*Tax_E*)	-	0.5 €/MWh (Orden IET/1045/2014, 2014)
- Tax on the remuneration of the generated energy (*Tax_R*)	-	7% (Orden

Accordingly, Fig. 8 illustrates the sensitivity analysis results by means of an area chart. The different uncertain input parameters are placed in the horizontal axis, and the vertical axis represents the economic impact of the parameter variations on the *EBITDA*, expressed as a percentage of the $EBITDA_{\_BS}$ reference value. In particular, warm-coloured areas represent the impact of positive variations in the input parameters with respect to the base scenario (orange-coloured for the +10% base scenario and yellow-coloured for the +5% base scenario). In the same way, the cold-coloured areas represent the impact caused by negative variations (dark-blue-coloured for the -10% base scenario and light-blue-coloured for the -5% base scenario).

Two different threshold limit values of selection have been employed when assessing the sensitivity analysis results, introducing an output/input variation ratio defined as the quotient of the *EBITDA* variation by the input parameter variation. One threshold corresponds to a more conservative and stringent scenario and the other threshold is associated to a less conservative scenario (see the input parameters framed with a red solid line and with a red dashed line in Fig. 8, respectively). Those parameters corresponding to ratios below the set thresholds are candidates for being disregarded in the simplified EMS model proposals (see Tables 4 and 5, respectively, for the sensitivity analysis definition and attained simplification of the EMS models under FIT and auction schemes).

The sensitivity analysis results as well as the obtained simplified model proposals under the two remuneration schemes here assessed are described below.



EBITDA sensitivity analysis results [%]
(a) Under RD 661/2007 FIT scheme
12%
10%
8%
6%
4%
2%
0%
-2%
-4%
-6%
-8%
-10%
-12%
K_R
Nh_inst_a+1
r_i
IPC
V_OMC_a+1
F_OMC_a+1
PHYSICAL
REGULATORY
ECONOMIC
(b) Under RD 413/2014 auction mechanism
4%
3%
2%
1%
0%
-1%
-2%
-3%
-4%
-5%
-6%
-7%
-8%
-9%
K_R
Nh_inst_a+1
LR
Δt_j
Δ_Std_Cost
K_RR
Pmf_i
LS2_ij
LS1_ij
LI1_ij
LI2_ij
SB_j
IPC
Pm_i
V_OMC_a+1
F_OMC_a+1
Tax_E
Tax_R
PHYSICAL
REGULATORY
ECONOMIC
+5% Base Case
+10% Base Case
-5% Base Case
-10% Base Case
Uncertain input parameters candidates to be neglected under the most conservative scenario
Uncertain input parameters candidates to be neglected under the less conservative scenario

Fig. 8. Impact of the uncertain parameters variation on the *EBITDA* under (a) RD 661/2007 FIT scheme, (b) RD 413/2014 auction mechanism. Source: self-elaboration.

5.1. Attainment of simplified model proposals under RD 661/2007 FIT scheme

Although RD 661/2007 FIT scheme is one of the simplest remuneration models, the possibility of simplifying it has been verified through the executed sensitivity analysis. According to the applied criteria (see Table 4), the implemented simplification has significantly reduced both the number of uncertain input parameters and the equations required in the EMS model.

Table 4

Sensitivity analysis definition and attained simplification of the EMS models under RD 661/2007 FIT scheme. Source: self-elaboration.

SFIT1 EMS model: the most conservative scenario		**Attained simplification**
Value of the output/input variation ratio used to disregard the uncertain parameters	Value ≤ 0.3/10	- 33% of the uncertain input parameters of the original EMS model are eliminated due to their low impact on the *EBITDA.* - 22% of reduction of input parameters of the original model. - 18% of reduction of the original equations. - To sum up, simplifying actions have been carried out on 36% of the equations (see Tables A.1 and A.2 and Fig. 9).
Parameters identification in Fig. 8	Input parameters framed with a red solid line in Fig. 8a	
Disregarded parameters	- The variable operating and maintenance cost within the year a+1 ($V\_OMC_{\_a+1}$) - The physical yearly degradation rate ($K_{\_R}$)	

SFIT2 EMS model: the less conservative scenario		**Attained simplification**
Value of the output/input variation ratio used to disregard the uncertain parameters	Value ≤ 0.9/10	- 50% of the uncertain input parameters of the original EMS model are neglected due to their low impact on the *EBITDA*. - 33% of reduction of input parameters of the original model. - 18% of reduction of the original equations. - To sum up, simplifying actions have been carried out on 45% of the equations (see Tables A.1 and A.2 and Fig. 10).
Parameters identification in Fig. 8	Input parameters framed with a red dashed line in Fig. 8a	
Disregarded parameters	- The variable operating and maintenance cost within the year a+1 ($V\_OMC_{\_a+1}$) - The physical yearly degradation rate ($K_{\_R}$) - The curtailment factor for *IPC* ($r_{\_i}$)	

The simplification study of the EMS model under RD 661/2007 FIT scheme has led to the attainment of two different simplified model proposals, namely, the model SFIT1 with four uncertain parameters in the most conservative scenario (see Fig. 9), and the model SFIT2 with three uncertain parameters in the less conservative scenario (see Fig. 10). The conceptual block diagrams depicting the simplified model proposals SFIT1 and SFIT2, in Figs. 9 and 10, respectively, follow the same format style previously explained for Figs. 6 and 7.

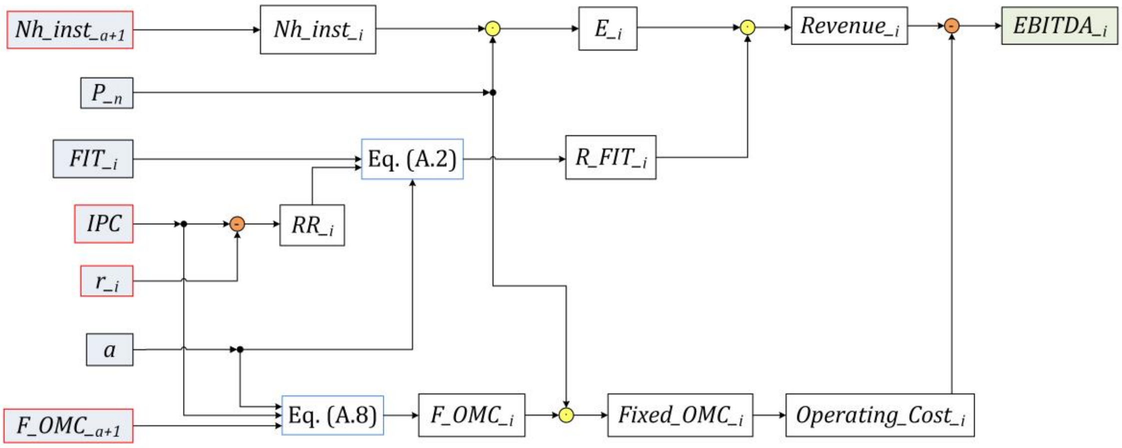


Fig. 9. Conceptual approach to the simplified EMS model proposal SFIT1 under RD 661/2007 FIT scheme. Source: self-elaboration.

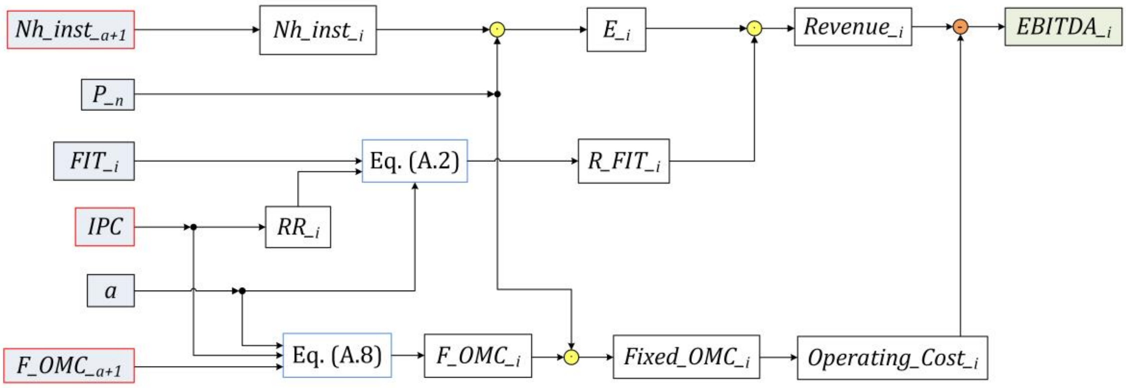


Fig. 10. Conceptual approach to the simplified EMS model proposal SFIT2 under RD 661/2007 FIT scheme. Source: self-elaboration.

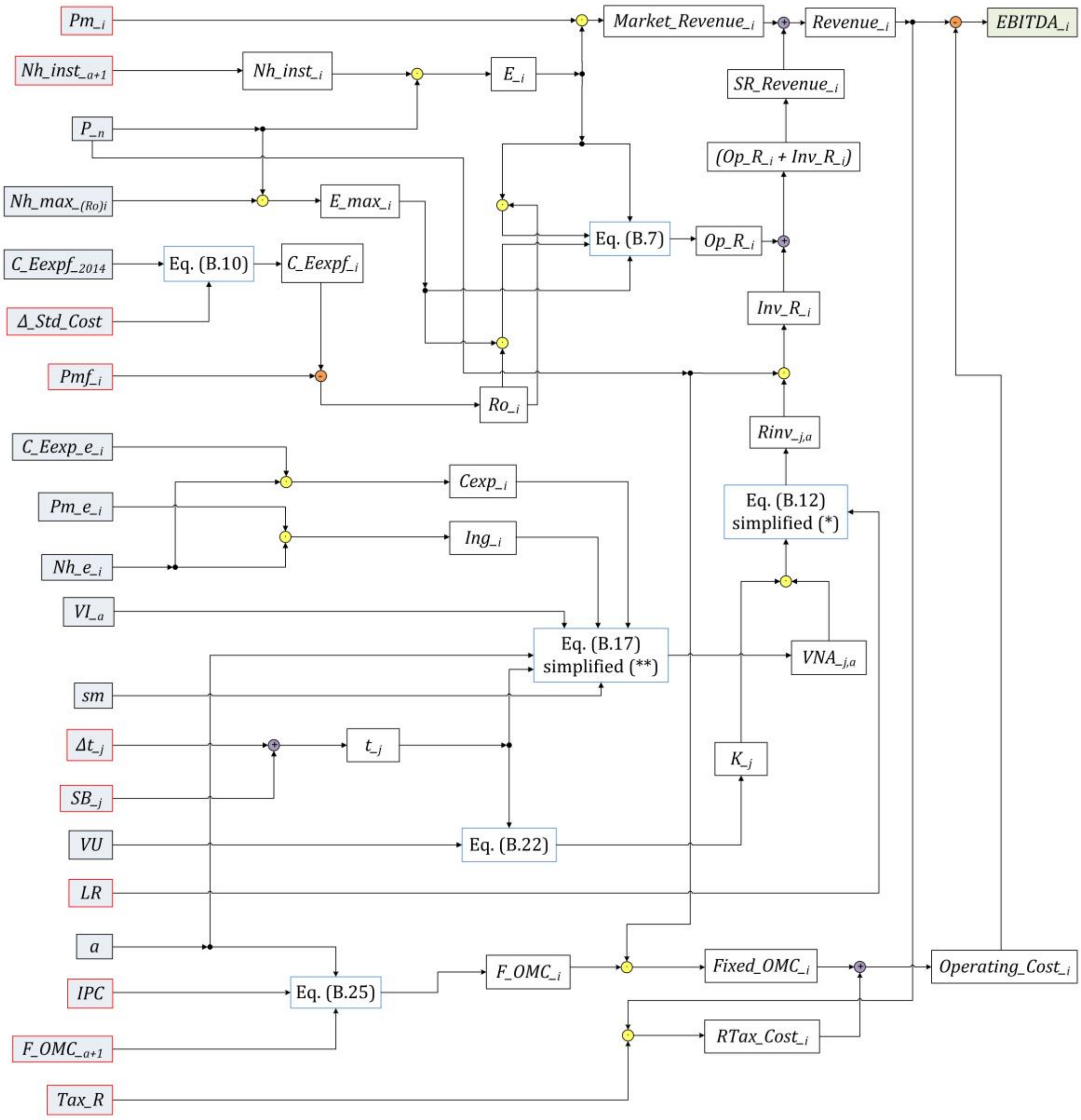
5.2. Attainment of simplified model proposals under RD 413/2014 auction mechanism

Based on the results of the sensitivity analysis simulation of the EMS model under RD 413/2014 auction mechanism, two simplified EMS model proposals are attained, i.e., S1 being the most conservative, with ten uncertain parameters (see Fig. 11), and S2 the less conservative, with eight uncertain parameters (see Fig. 12). The conceptual block diagrams depicting the simplified model proposals S1 and S2 in Figs. 11 and 12, respectively, follow the same format style previously explained for Figs. 6, 7, 9 and 10. In this regard, the criteria and the simplification attainment are depicted in Table 5, where it is found that the executed simplification has considerably reduced both the number of uncertain input parameters and the equations required in the EMS model under the auction mechanism.

Table 5
Sensitivity analysis definition and attained simplification of the EMS models under RD 413/2014 auction mechanism. Source: self-elaboration.

<table>
<tr><th colspan="2">S1 EMS model: the most conservative scenario</th><th>Attained simplification</th></tr>
<tr><td>Value of the output/input variation ratio used to disregard the uncertain parameters</td><td>Value ≤ 0.2/10</td><td rowspan="3">- 44% of the uncertain input parameters of the original EMS model are eliminated due to their low impact on the EBITDA.
- 35% of reduction of input parameters of the original model.
- 30% of reduction of the original equations.
- To sum up, simplifying actions have been carried out on 47% of the equations (see Tables B.1 and B.2 and Fig. 11).</td></tr>
<tr><td>Parameters identification in Fig. 8</td><td>Input parameters framed with a red solid line in Fig. 8b</td></tr>
<tr><td>Disregarded parameters</td><td>- The variable operating and maintenance cost within the year a+1 (V_OMC_{a+1})
- The physical yearly degradation rate (K_R)
- The standard yearly degradation rate regulatory established (K_{RR})
- The lower and the upper limits ($LS2_{i,j}$, $LS1_{i,j}$, $LI1_{i,j}$, $LI2_{i,j}$) regulatory set for the computation of $Vajdm_{i,j}$
- The economic tax on the generated energy (Tax_E)</td></tr>
</table>

<table>
<tr><th colspan="2">S2 EMS model: the less conservative scenario</th><th>Attained simplification</th></tr>
<tr><td>Value of the output/input variation ratio used to disregard the uncertain parameters</td><td>Value ≤ 0.6/10</td><td rowspan="3">- 56% of the uncertain input parameters of the original EMS model are neglected due to their low impact on the EBITDA.
- 42% of reduction of input parameters of the original model.
- 30% of reduction of the original equations.
- To sum up, simplifying actions have been carried out on 53% of the equations (see Tables B.1 and B.2 and Fig. 12).</td></tr>
<tr><td>Parameters identification in Fig. 8</td><td>Input parameters framed with a red dashed line in Fig. 8b</td></tr>
<tr><td>Disregarded parameters</td><td>- The variable operating and maintenance cost within the year a+1 (V_OMC_{a+1})
- The physical yearly degradation rate (K_R)
- The standard yearly degradation rate regulatory established (K_{RR})
- The lower and the upper limits ($LS2_{i,j}$, $LS1_{i,j}$, $LI1_{i,j}$, $LI2_{i,j}$) regulatory set for the computation of $Vajdm_{i,j}$
- The economic tax on the generated energy (Tax_E)
- The annual increase in standard operating cost per unit of generated energy regulatory set (Δ_Std_Cost)
- The consumer price index (IPC)</td></tr>
</table>



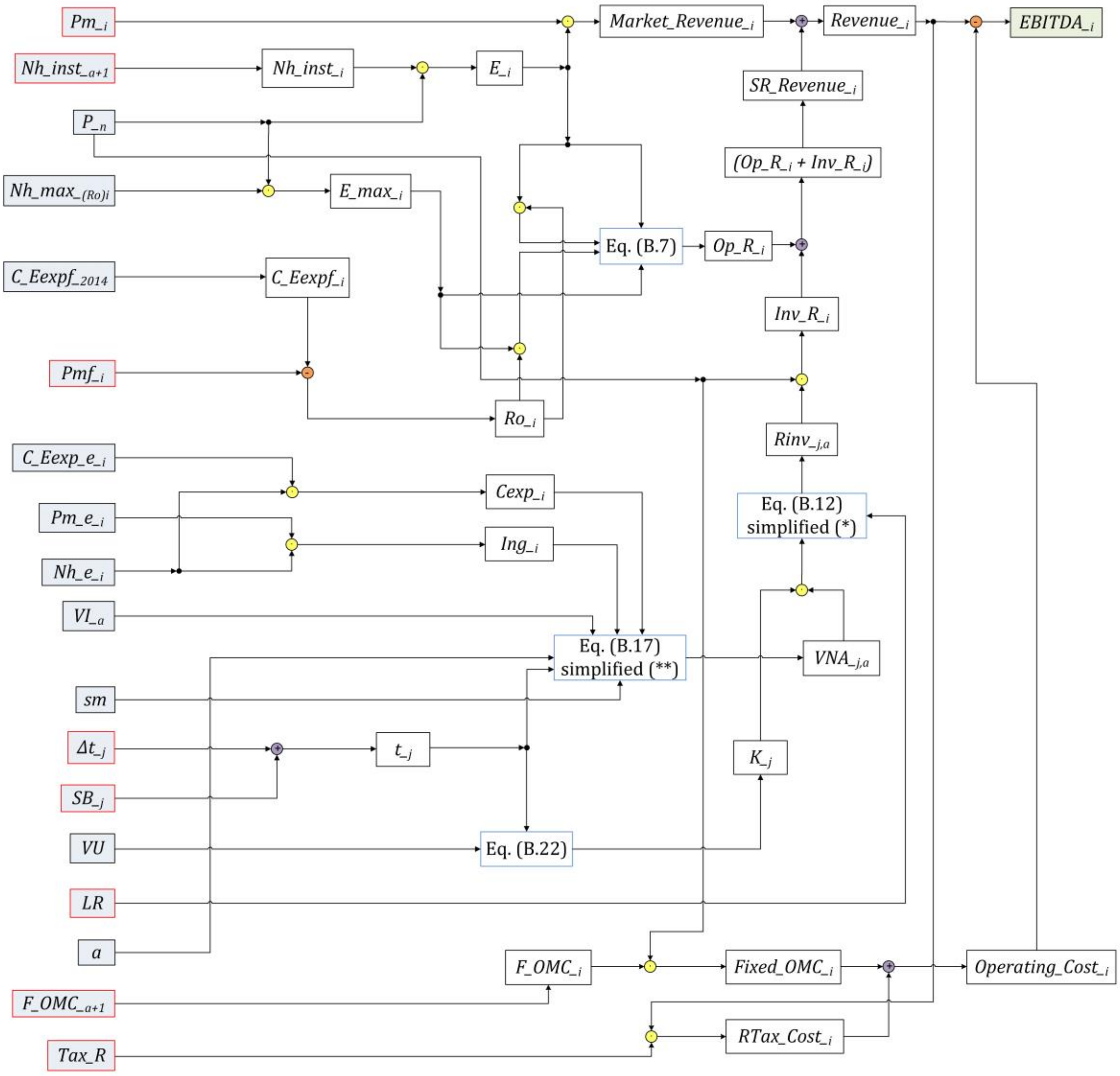
(*)

$$Rinv_{\_j,a} = \begin{cases} VNA_{\_j,a} \cdot K_{\_j}, & PT\_IRR_{\_i} \le LR \\ 0, & PT\_IRR_{\_i} > LR \end{cases}$$

(**)

$$VNA_{\_j,a} = \begin{cases} VI_{\_a} \cdot \left(1 + t_{\_j}\right)^{p-a-1} - \sum_{i=a+1}^{p-1} \left(Ing_{\_i} - Cexp_{\_i}\right) \cdot \left(1 + t_{\_j}\right)^{p-i-1}, & j = 1 \\ VNA_{\_j-1,a} \cdot \left(1 + t_{\_j-1}\right)^{sm}, & j > 1 \end{cases}$$

Fig. 11. Conceptual approach to the simplified EMS model proposal S1 under RD 413/2014 auction mechanism. Source: self-elaboration.



(*)

$$Rinv_{\_j,a} = \begin{cases} VNA_{\_j,a} \cdot K_{\_j}, & PT\_IRR_{\_i} \leq LR \\ 0, & PT\_IRR_{\_i} > LR \end{cases}$$

(**)

$$VNA_{\_j,a} = \begin{cases} VI_{\_a} \cdot (1+t_{\_j})^{p-a-1} - \sum_{i=a+1}^{p-1} (Ing_{\_i} - Cexp_{\_i}) \cdot (1+t_{\_j})^{p-i-1}, & j = 1 \\ VNA_{\_j-1,a} \cdot (1+t_{\_j-1})^{sm}, & j > 1 \end{cases}$$

Fig. 12. Conceptual approach to the simplified EMS model proposal S2 under RD 413/2014 auction mechanism. Source: self-elaboration.

6. Monte Carlo simulation for the validation of simplified model proposals

Following the procedure defined in Fig. 5 for Step 3 of the present simplifying methodology, the MC simulation of the case study is applied to the original and the simplified EMS models under the different remuneration mechanisms by randomly and simultaneously varying the uncertain input parameters of the second group, while the parameters of the first group "DATA" remain constant.

The randomness introduced in these uncertain parameters through a triangular PDF in the case study MC simulation aims to take into account the inherent risk of each remuneration scheme due to physical, economic or regulatory changes in the EMS analysis. In this way, the impacts of the uncertainties and variabilities existing in the EMS can be considered in the mid and long-term energy management strategy of these renewable assets.

Table 6 shows the characterization of the triangular PDF defining each of the uncertain input parameters under both remuneration mechanisms, by means of its base scenario value and its variation interval between the minimum and the maximum expected values. The setting of each variation interval is based on the historical trends of each parameter, as well as on its evolution perspectives in the coming years.

Specifically, it is important to highlight that under the highly complex RD 413/2014 auction mechanism some of its uncertain input parameters set in a regulatory manner can be reviewed and updated every three-year regulatory half-period or every six-year regulatory period. In the same way, other economic parameters such as $Pm_{\_i}$ are updated annually. Thus, these uncertain input parameters are varied more than once by MC sample over the facility useful life.

Table 6
Characterization of the uncertain input parameters considered in the MC simulation of a CSP facility under RD 661/2007 FIT scheme and RD 413/2014 auction mechanism. Source: self-elaboration.

Parameters	**RD 661/2007 FIT scheme**		**RD 413/2014 auction mechanism**	
	Base scenario values	**Intervals of variation**	**Base scenario values**	**Intervals of variation**
Physical parameters				
- Physical degradation rate ($K_{\_R}$)	0.2%	[0.2, 0.5] %	0.2%	[0.2, 0.5] %
- Initial equivalent operating hours ($Nh\_inst_{\_a+1}$)	1,873 h	[1700, 2000] h	1,873 h	[1700, 2000] h
Regulatory parameters				
- Curtailment for *IPC* ($r_{\_i}$)	0.25%	[0, 0.5] %	-	-
- Reasonable profitability (*LR*)	-	-	7.398%	[4, 8] %
- Differential added to $SB_{\_j}$ ($\Delta t_{\_j}$)	-	-	3%	[1, 5] %

- Increment in standard operating cost (*Δ_Std_Cost*)	-	-	1%	[1, 2.5] %
- Standard degradation rate (K_{RR})	-	-	0.2%	[0.2, 0.5] %
- Future estimated average market price (Pmf_i)	-	-	48.75 €/MWh	[40, 60] €/MWh
- Second upper limit related to the deviations adjustment of Pm_i and Pmf_i ($LS2\_{i,j}$)	-	-	54.04 €/MWh	[45, 65] €/MWh
- First upper limit related to the deviations adjustment of Pm_i and Pmf_i ($LS1\_{i,j}$)	-	-	50.29 €/MWh	[40, 60] €/MWh
- First lower limit related to the deviations adjustment of Pm_i and Pmf_i ($LI1\_{i,j}$)	-	-	42.78 €/MWh	[35, 55] €/MWh
- Second lower limit related to the deviations adjustment of Pm_i and Pmf_i ($LI2\_{i,j}$)	-	-	39.03 €/MWh	[30, 50] €/MWh
Economic parameters				
- Average yield of the 10-year Spanish bonds (SB_j)	-	-	3.94%	[1, 5] %
- Consumer price index (*IPC*)	2.05%	[0, 4] %	2.05%	[0, 4] %
- Average electricity market price (Pm_i)	-	-	46.75 €/MWh	[35, 60] €/MWh
- Initial variable operating and maintenance cost (V_OMC_{a+1})	2.57 €/MWh	[0, 5] €/MWh	2.57 €/MWh	[0, 5] €/MWh
- Initial fixed operating cost (F_OMC_{a+1})	59.89 €/kW	[50, 80] €/kW	59.89 €/kW	[50, 80] €/kW
- Tax on the generated energy (*Tax_E*)	-	-	0.5 €/MWh	[0, 1] €/MWh
- Tax on the remuneration of the generated energy (*Tax_R*)	-	-	7%	[0, 10] %

Tables 7 and 8 depict the *EBITDA* detailed results of the most representative statistics obtained from the case study MC simulation for each of the EMS models under the different remuneration mechanisms. In turn, Figs. 13 and 14 show the probability histograms for the *EBITDA* when performing the MC simulation of the original and the simplified EMS models under the analysed remuneration schemes.

For the validation and selection of the simplified models, an error equal to or lower than 10% has been defined as the threshold limit accuracy level. Thus, those simplified model proposals with generalised errors in the *EBITDA* greater than 10% are discarded, while those with errors below 10% are accepted as feasible simplifications of the original EMS model.

6.1. Validation and selection of simplified model proposals under RD 661/2007 FIT scheme

On one side, when comparing the mean MC results obtained under the simplified model proposal SFIT1 with the reference results (see Table 7), it can be denoted the existence of an error of 5.39% in the mean value of the *EBITDA*, displacing its histogram to the right (see the yellow-coloured curve in Fig. 13). In this vein, it is determined that the error obtained in the values defining the first quartile (Q1 – 25th percentile), that is, where 25% of the *EBITDA* results are located, and the third quartile (Q3 – 75th percentile), namely, where 75% of *EBITDA* results are found, is 5.62% and 5.53%, respectively. While the error computed in the value representing the *EBITDA* interquartile range (IQR), that is, the distance between Q1 and Q3, is 5.19%, denoting a bit more dispersion in the results. In addition, the error obtained in both the standard deviation of the *EBITDA* regarding the mean and in the 95% confidence interval of the mean is 5.16%, with respect to the value of these statistics under the original EMS model.

On the other side, when comparing the mean results achieved under the simplified model proposal SFIT2 with the reference results (see Table 7), it is observed an error of 15.32% in the mean value of the *EBITDA*, also displacing its histogram steeply to the right (see the orange-coloured curve in Fig. 13). Accordingly, it is estimated that the error obtained in the values defining Q1 and Q3 is 15.58% and 15.48%, respectively. While the error computed in the value representing the *EBITDA* IQR is 15.07%, indicating quite more scattered results. Moreover, the error computed in both the standard deviation of the *EBITDA* regarding the mean and in the 95% confidence interval of the mean is 13.26% with respect to the values of these statistics under the original EMS model.

Table 7
EBITDA statistics from the MC simulation of the EMS models under RD 661/2007 FIT scheme. Source: self-elaboration.

Statistics – EBITDA [M€]	**Original EMS model** (Reference results)	**Simplified model proposals based on the sensitivity analysis approach**	
		Most conservative approach (SFIT1)	**Less conservative approach (SFIT2)**
Mean [M€]	616.04	649.23	710.42
Standard Deviation [M€]	100.06	105.22	113.33

Confidence interval (acceptance level 95%) [M€]	1.96	2.06	2.22
Q1 [M€]	541.74	572.18	626.14
Q3 [M€]	680.99	718.66	786.38
IQR [M€]	139.25	146.48	160.24
Minimum [M€]	379.45	405.26	449.43
Maximum [M€]	986.63	989.15	1,074.52
Sample Total number	10,000	10,000	10,000
Computing time [h]	3.50	3.25	3.00

Note: The computer used to perform the MC simulation of the EMS models under RD 661/2007 FIT scheme has the following characteristics: Intel(R) Core(TM) i3-2310M CPU @ 2.10GHz 2.10GHz; 8.00GB RAM; 64-bit operating system Windows.

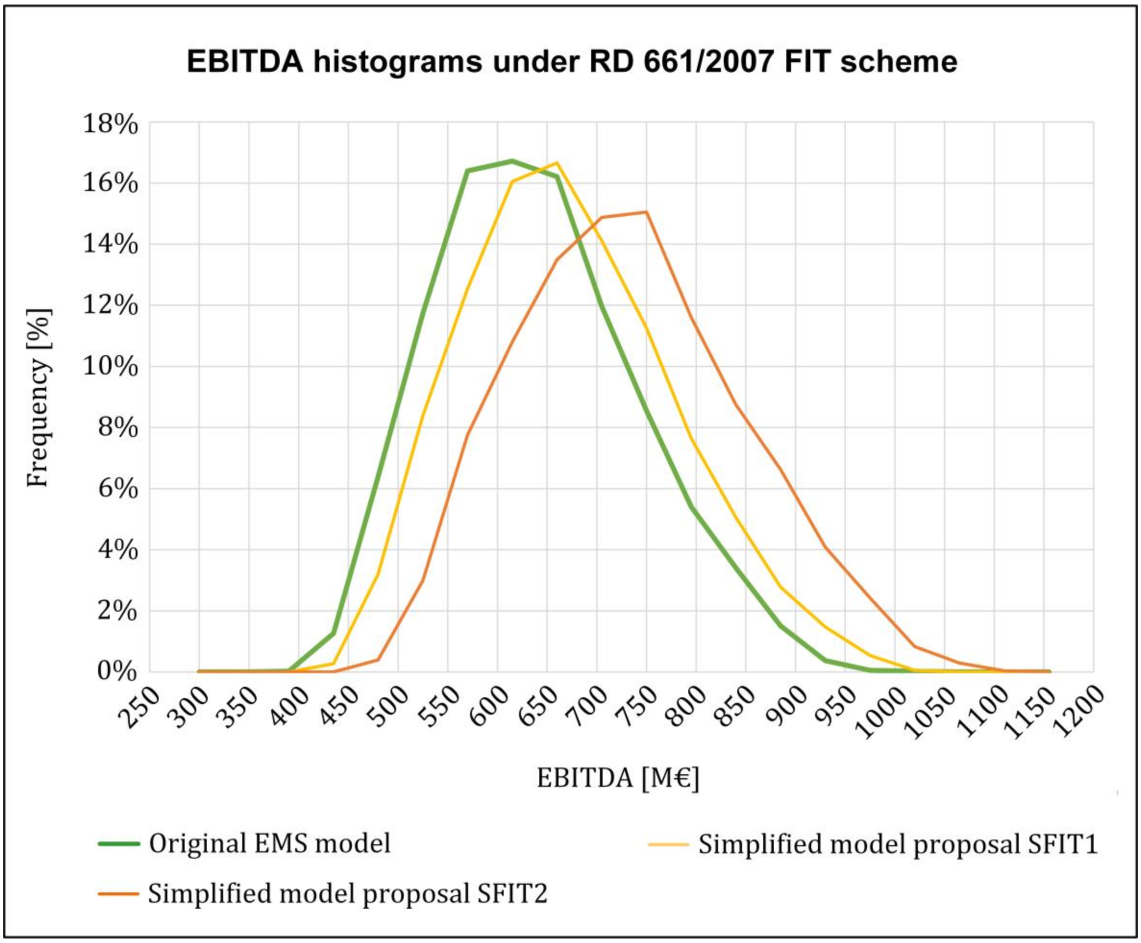


Fig. 13. *EBITDA* histograms for the EMS models under RD 661/2007 FIT scheme. Source: self-elaboration.

In addition to analysing the average *EBITDA* results obtained in the EMS models under RD 661/2007 FIT scheme (see Table 7), the *EBITDA* relative errors ($EBITDA\_Relative\_Error(RD\ 661/2007)_{ns}$) for each MC sample (*ns*) have also been computed by applying Eq. (3) in such a way that it is possible to validate the existence of extreme scenario results for which the simplified EMS models may not work:

$$EBITDA\_Relative\_Error(RD\ 661/2007)_{ns} = \frac{|EBITDA\_Simplified\_EMS_{ns} - EBITDA\_Original\_EMS_{ns}|}{EBITDA\_Original\_EMS_{ns}} \quad (3)$$

Thus, it can be verified that indeed the SFIT1 model presents errors in all the MC samples around the mean value of 5.39% previously indicated. Specifically, in 99.8% of the MC samples the relative error is between 4.65% and 6.30%. In turn, it is also checked that the SFIT2 model presents errors in all the MC samples around the mean value of 15.32% aforementioned. Specifically, in 99.3% of the MC samples the relative error is between 13.73% and 16.20%.

In short, as it has been verified that the simplified model proposal SFIT1 presents generalised errors well below the 10% threshold limit accuracy level with respect to the original EMS model, it is therefore selected. Accordingly, this model proposal is expected to be a useful tool for the SCSPS to provide a better understanding of the impact of the remaining uncertain parameters on the CSP energy assets in the mid and long term. Similarly, this model SFIT1 is expected to be easier to linearize, helping the process of the energy management model formulation. By contrast, the simplified model proposal SFIT2 presents generalised errors around 15%, and consequently, it is discarded.

6.2. Validation and selection of simplified model proposals under RD 413/2014 auction mechanism

On the one hand, when comparing the mean results obtained under the simplified model proposal S1 with the reference results (see Table 8), it can be denoted the existence of an error of 3.27% in the mean value of the *EBITDA*, displacing its histogram to the right (see the yellow-coloured curve in Fig. 14). In this sense, it is determined that the error obtained in the values defining Q1 and Q3 is 3.45% and 3.05%, respectively. While the error computed in the value representing the *EBITDA* IQR is 0.31%, denoting more dispersion in the results. In addition, the error obtained in the standard deviation of the *EBITDA* regarding the mean is 0.18% with respect to the value of this statistic under the original EMS model. Similarly, as for the 95% confidence interval of the mean, it is also observed an error of 0.18%.

On the other hand, when comparing the mean results achieved under the simplified model proposal S2 with the reference results (see Table 8), it is observed an error of 3.82% in the mean value of the *EBITDA*, also displacing its histogram to the right (see the orange-coloured curve in Fig. 14). In this vein, it is estimated that the error obtained in the values defining Q1 and Q3 is 4.26% and 3.46%, respectively. While the error computed in the value representing the *EBITDA* IQR is -2.02%, indicating rather less scattered results. Moreover, the error computed in both the standard deviation of the *EBITDA* regarding the mean and in the 95% confidence interval of the mean is -4.14% with respect to the values of these statistics under the original EMS model.

Table 8
EBITDA statistics from the MC simulation of the EMS models under RD 413/2014 auction mechanism. Source: self-elaboration.

Statistics – EBITDA [M€]	**Original EMS model** (Reference results)	**Simplified model proposals based on the sensitivity analysis approach**	
		Most conservative approach (S1)	**Less conservative approach (S2)**
Mean [M€]	449.94	464.66	467.13
Standard Deviation [M€]	40.00	40.07	38.34
Confidence interval (acceptance level 95%) [M€]	0.78	0.79	0.75
Q1 [M€]	419.42	433.87	437.29
Q3 [M€]	480.66	495.31	497.30
IQR [M€]	61.24	61.44	60.01
Minimum [M€]	322.15	328.40	349.27
Maximum [M€]	586.00	581.85	573.08
Sample Total number	10,000	10,000	10,000
Computing time [h]	10.50	8.50	7.00

Note: The computer used to perform the MC simulation of the EMS models under RD 413/2014 auction scheme has the following characteristics: Intel(R) Core(TM) i3-2310M CPU @ 2.10GHz 2.10GHz; 8.00GB RAM; 64-bit operating system Windows.

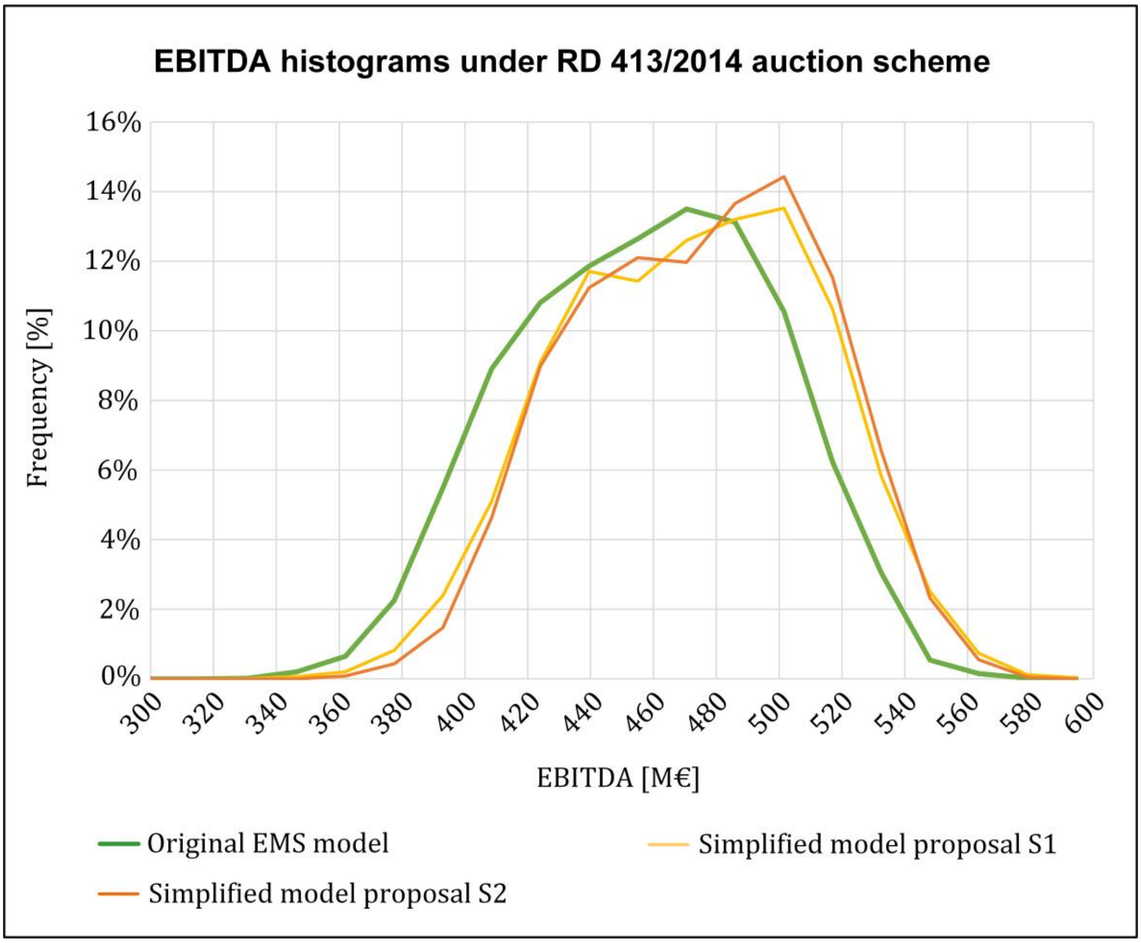


Fig. 14. *EBITDA* histograms for the EMS models under RD 413/2014 auction scheme. Source: self-elaboration.

In addition to analysing the average *EBITDA* results obtained in the EMS models under RD 413/2014 auction scheme (see Table 8), the *EBITDA* relative errors ($EBITDA\_Relative\_Error(RD\ 413/2014)_{ns}$) for each MC sample (*ns*) have also been computed by applying Eq. (4) in such a way that it is possible to validate the existence of extreme scenario results for which the simplified EMS models may not work:

$$EBITDA\_Relative\_Error(RD\ 413/2014)_{ns} = \frac{|EBITDA\_Simplified\_EMS_{ns} - EBITDA\_Original\_EMS_{ns}|}{EBITDA\_Original\_EMS_{ns}} \quad (4)$$

Thus, it can be verified that indeed the S1 model presents errors in all the MC samples around the mean value of 3.27% previously indicated. Specifically, in 99.9% of the MC samples the relative error is between 2.25% and 4.05%. In turn, it is also checked that the S2 model presents errors in all the MC samples around the mean value of 3.82% aforementioned. Specifically, in 99.4% of the MC samples the relative error is between 2.25% and 6.30%.

On balance, from the analysis of the results obtained from the MC simulation of the case study under RD 413/2014 auction mechanism, it has been verified that the two simplified model proposals S1 and S2 present generalised errors substantially below the 10% threshold limit accuracy level with respect to the original EMS model. Accordingly, both model proposals are selected, and are expected to be a useful tool for the SCSPS as they provide a better understanding of the impact of the remaining uncertain parameters on the CSP energy assets in the mid and long term. Likewise, the new simplified EMS models S1 and S2 are expected to be easier to linearize, helping the process of the EMS model formulation.

7. Energy management long term strategy

7.1. Attainment of the optimal energy management long term strategy

7.1.1. Under RD 661/2007 scheme

The FIT scheme is a remuneration mechanism based solely on energy production. In general, the revenue of this kind of remuneration relies on the perceived *R_FIT* ($R\_FIT_{\_i,d,h}$) of the produced energy within an hour *h* on a particular day *d* of the year *i* ($E_{\_i,d,h}$). Consequently, the *EBITDA* will be equal to this revenue minus the variable and fixed operating costs:

$$EBITDA_{\_i,d,h} = E_{\_i,d,h} \cdot R\_FIT_{\_i,d,h} - E_{\_i,d,h} \cdot V\_OMC_{\_i,d,h} - P_n \cdot F\_OMC_{\_i,d,h} \quad (5)$$

Let us assume that a generic power plant has a maximum number of equivalent operating hours ($Nh\_inst\_max_{\_i}$) within a year *i*. During these hours the rated power is generated within the time step of 1 hour (ΔT) due to the availability of the renewable energy resource. In view of this set of available hours, energy management should decide whether to operate or not the power plant within a particular hour. This decision is derived from the binary variable $y_{\_i,d,h}$, which is activated ($y_{\_i,d,h}$ =1) if it is decided to operate the power plant:

$$E_{\_i,d,h} = P_n \cdot \Delta T \cdot y_{\_i,d,h} \quad (6)$$

As a result, the effective number of operating hours *Nh_inst_i* can be described as:

$$Nh\_inst_{\_i} = \sum_d \sum_h y_{\_i,d,h} \cdot \Delta T \quad (7)$$

$$0 \leq Nh\_inst_{\_i} \leq Nh\_inst\_max_{\_i} \tag{8}$$

It must be noted that when the plant is not operated, there are neither revenue nor variable operating and maintenance cost, but only the fixed operating cost:

$$EBITDA_{\_i,d,h}\big|_{y_{\_i,d,h}=0} = -P_n \cdot F\_OMC_{\_i,d,h} \tag{9}$$

Generally, the optimal decision maximizing the *EBITDA* for a particular hour depends on the value of the subtraction between $R\_FIT_{\_i,d,h}$ and $V\_OMC_{\_i,d,h}$ (see Eq. (10)). In the case of being $V\_OMC_{\_i,d,h}$ higher than $R\_FIT_{\_i,d,h}$, it could be advisable not to operate the plant to avoid the increase of the negative value of the *EBITDA*. Only when energy price is higher is when the plant might be operated.

$$EBITDA_{\_i,d,h} = P_n \cdot \Delta T \cdot y_{\_i,d,h} \cdot \left(R\_FIT_{\_i,d,h} - V\_OMC_{\_i,d,h}\right) - P_n \cdot F\_OMC_{\_i,d,h} \tag{10}$$

Using the SFIT1 EMS model for the case study under RD 661/2007 FIT scheme, where the parameter *V_OMC* was disregarded, the resulting simplified expression for the *EBITDA* is described in Eq. (11). Hence the optimal strategy is to operate the maximum number of hours $Nh\_inst\_max_{\_i}$ within the year (see Eq. (12)):

$$EBITDA_{\_i,d,h} = P_n \cdot \Delta T \cdot y_{\_i,d,h} \cdot R\_FIT_{\_i,d,h} - P_n \cdot F\_OMC_{\_i,d,h} \tag{11}$$

$$EBITDA_{\_i} = \sum_d \sum_h EBITDA_{\_i,d,h} = P_n \cdot Nh\_inst\_max_{\_i} \cdot R\_FIT_{\_i} - P_n \cdot F\_OMC_{\_i} \tag{12}$$

7.1.2. Under RD 413/2014 auction mechanism

The image of Fig. 7 allows illustrating how difficult it might be to deduce the optimal long-term energy management strategy for a power plant under RD 413/2014 auction mechanism. The difficulty relies on the complexity of the specific remuneration mechanism and its huge economic weight on the power plant revenue. According to the analysis results, the $SR\_Revenue_{\_i}$ accounts for 85% of the total incomes. Hence, it is important to analyse whether the long-term energy production strategy might harm its results.

Although the objective of the analysis is focused on the long-term strategy, as happened in the previous section, the first step will be to provide the *EBITDA* hourly defined:

$$EBITDA\_{i,d,h} = Market\_Revenue\_{i,d,h} + SR\_Revenue\_{i,d,h} - Fixed\_OMC\_{i,d,h} - Variable\_OMC\_{i,d,h} - ETax\_Cost\_{i,d,h} - RTax\_Cost\_{i,d,h} \quad (13)$$

As the attention on the revenues and costs derived from the energy production is a must to understand the optimal strategy, Eq. (13) is rearranged. In Eq. (14) it has been assumed that the maximum value of the variable d_i modulating $SR\_Revenue\_{i,d,h}$ has been achieved (d_i =1, see Eq. (B.6)). To this aim the manager of the power plant has to guarantee that Nh_inst_i is greater than Nh_min_i and according to Eq. (B.5) the *EBITDA* results in:

$$EBITDA\_{i,d,h} = P_n \cdot \Delta T \cdot y\_{i,d,h} \cdot \left[\left(Pm\_{i,d,h} + Ro\_{i,d,h}\right) - \left(V\_OMC\_{i,d,h} + Tax\_E\right)\right] + Inv\_R\_{i,d,h} - RTax\_Cost\_{i,d,h} - Fixed\_OMC\_{i,d,h} \quad (14)$$

Nevertheless, the complexity remains the same as the inner relations between the equations that lead to the formation of the value Inv_R_i hamper the analysis of whether a particularly long-term strategy is suitable for the energy asset. Besides, due to the enormous impact (about 80%) that Inv_R_i has on the total amount of the $SR\_Revenue\_i$, it is essential to base this strategy on facts rather than mere assumptions. As a result, the simplified models S1 and S2 derived from applying the proposed methodology help to surpass this complexity by obtaining the simplest possible expression of the Inv_R_i:

$$Inv\_R\_i = P_n \cdot VNA\_{j-1,a} \cdot \left(1 + t\_{j-1}\right)^{sm} \cdot \frac{t\_j \cdot \left(1+t\_j\right)^{VR\_j}}{\left(1+t\_j\right)^{VR\_j} - 1} \quad (15)$$

In this regard, Eq. (15) provides evidence that denies any relation between the operating strategy and the investment remuneration, which helps to clarify and simplify the energy asset management.

Besides, based as well on these simplified models, the parameters *V_OMC* and *Tax_E* can also be disregarded, and Eq. (14) can be expressed as follows:

$$EBITDA_{\_i,d,h} = P_n \cdot \Delta T \cdot y_{\_i,d,h} \cdot \left(Pm_{\_i,d,h} + Ro_{\_i,d,h}\right) + \frac{1}{8760} \cdot P_n \cdot VNA_{\_j-1,a} \cdot \left(1 + t_{\_j-1}\right)^{sm} \cdot \frac{t_{\_j} \cdot \left(1 + t_{\_j}\right)^{VR_{\_j}}}{\left(1 + t_{\_j}\right)^{VR_{\_j}} - 1} - RTax\_Cost_{\_i,d,h} - Fixed\_OMC_{\_i,d,h} \quad (16)$$

Hence, the *EBITDA* within a year *i* after the first semi period obtained by applying the proposed methodology follows:

$$EBITDA_{\_i} = P_n \cdot \left\{ (1 - Tax\_R) \cdot \left[\sum_d \sum_h \Delta T \cdot y_{\_i,d,h} \cdot \left(Pm_{\_i,d,h} + Ro_{\_i,d,h}\right) + VNA_{\_j-1,a} \cdot \left(1 + t_{\_j-1}\right)^{sm} \cdot \frac{t_{\_j} \cdot \left(1 + t_{\_j}\right)^{VR_{\_j}}}{\left(1 + t_{\_j}\right)^{VR_{\_j}} - 1} \right] - \left[(1 + IPC)^{i-1} \cdot F\_OMC_{\_i}\right] \right\} \quad (17)$$

In this regard, Eq. (17) clearly contributes to understanding the implications of the long-term operating management strategy on the revenue and costs, surpassing the complexity depicted by Fig. 7, as it can identify which revenue does not depend on the operation strategy, i.e., the *VNA* and $t_{\_j}$.

Eq. (17) provides valuable information on managing the plant to maximize the revenues related to its operation. As the income from the operation (market and operation remuneration) is proportional to the equivalent hours *Nh_inst_i*, Eq. (17) clearly indicates that the greater number of worked equivalent hours, the better. Therefore the binary variable $y_{\_i,d,h}$ will always be activated (see Eq. (18)).This strategy is also reinforced by the results provided in Fig. 8, where it is proved that the weight of *Nh_inst_i* is greater than the weight of *F_OMC_i* regarding the *EBITDA* results.

$$EBITDA_{\_i} = P_n \cdot \left\{ (1 - Tax\_R) \cdot \left[\sum_d \sum_h \Delta T \cdot Pm_{\_i,d,h} + Nh\_inst\_max_{\_i} \cdot Ro_{\_i} + VNA_{\_j-1,a} \cdot \left(1 + t_{\_j-1}\right)^{sm} \cdot \frac{t_{\_j} \cdot \left(1 + t_{\_j}\right)^{VR_{\_j}}}{\left(1 + t_{\_j}\right)^{VR_{\_j}} - 1} \right] - \left[(1 + IPC)^{i-1} \cdot F\_OMC_{\_i} \right] \right\} \tag{18}$$

Although the long-term energy management strategy of working the maximum hours is the same as for the FIT scheme, this apparently obvious result is not evident from the complex remuneration model in Eq. (B.1) to Eq. (B.29). It has been by applying the proposed simplification methodology that this energy management strategy has been founded with a strong basis.

7.2. Assessing the economic results of the optimal energy management long term strategy

Once the optimal energy management long term strategy is determined, it is time to assess its economic results. A simple but straightforward way to evaluate the economic results of the energy asset is through the fixed charge rate (*FCR*). According to the literature, *FCR* allows determining the amount of revenue per euro investment to recover the investment cost (*IC*). In this regard, given an expected *FCR* of an energy asset with a known *IC*, the revenues of this asset through its useful lifetime (*ULT*) should be greater o equal to:

$$\sum_{i=1}^{ULT} Revenue_{\_i} = FCR \cdot IC \cdot ULT \tag{19}$$

Considering the *IC* on the energy asset as a way to obtain a gradual uniform stream of repayment each year, the total stream of repayment (*TSR*) through the *ULT* can be expressed as follows:

$$TSR = UCRF \cdot IC \cdot ULT \tag{20}$$

Where the uniform capital recovery factor (*UCRF*) is defined as:

$$UCRF = \frac{dr \cdot (1 + dr)^{ULT}}{(1 + dr)^{ULT} - 1} \tag{21}$$

Being *dr*, the discounted rate associated with the *UCRF*.

Considering a no-tax investment scenario, both *FCR* and *UCRF* can be formulated together as follows:

$$FCR = UCRF + Pc \tag{22}$$

Where the annual cost as a percentage of the *IC* is depicted by *Pc*.

According to Eq. (22), this relation can be expressed through the *ULT* as follows:

$$(FCR - Pc) \cdot IC \cdot ULT = UCRF \cdot IC \cdot ULT \tag{23}$$

$$\sum_{i=1}^{ULT} EBITDA_{\_i} = UCRF \cdot IC \cdot ULT \tag{24}$$

And according to Eq. (24), each one of the economic schemes possesses a specific *UCRF*:

$$UCRF_{RD\ 661/2007} = \frac{1}{IC \cdot ULT} \cdot \sum_{i=1}^{ULT} (P_n \cdot Nh\_inst\_max_{\_i} \cdot R\_FIT_{\_i} - P_n \cdot F\_OMC_{\_i}) \tag{25}$$

$$UCRF_{RD\ 413/2014} =$$

$$\frac{1}{IC \cdot ULT} \cdot \sum_{i=1}^{ULT} P_n \cdot \Bigg\{ (1 - Tax\_R) \cdot \left[\sum_{d} \sum_{h} \Delta T \cdot Pm_{-i,d,h} + Nh\_inst\_max_{-i} \cdot Ro_{-i} + VNA_{-j-1,a} \cdot \left(1 + t_{-j-1}\right)^{sm} \cdot \frac{t_{-j} \cdot \left(1 + t_{-j}\right)^{VR_{-j}}}{\left(1 + t_{-j}\right)^{VR_{-j}} - 1} \right] - \left[(1 + IPC)^{i-1} \cdot F\_OMC_{-i} \right] \Bigg\} \quad (26)$$

Although having established the optimal energy management strategy, the uncertainty on the energy asset remains and may affect its financial results. In this regard, a what-if scenario analysis has been undertaken using Eqs. (25) and (26) to determine the range of the possible financial results in this uncertain context. According to it, Fig. 15 depict the expected values of *UCRF* and *dr* for the energy asset under both economic schemes.

Five different what-if scenarios have been defined taking into account the range of possible values of the uncertain input parameters under both remuneration mechanisms (see Table 6). Specifically, a Base Case scenario, two extreme cases, i.e., the Worst Case and the Best Case, and two intermediate scenarios between the Base Case and the extremes, i.e., the Intermediate-Worst Case and the Intermediate-Best Case, have been analysed.

For the 50 MW CSPP here analysed, it has been considered an *ULT* of 25 years and an *IC* of 228.805 M€, according to the data extracted from Table 2.

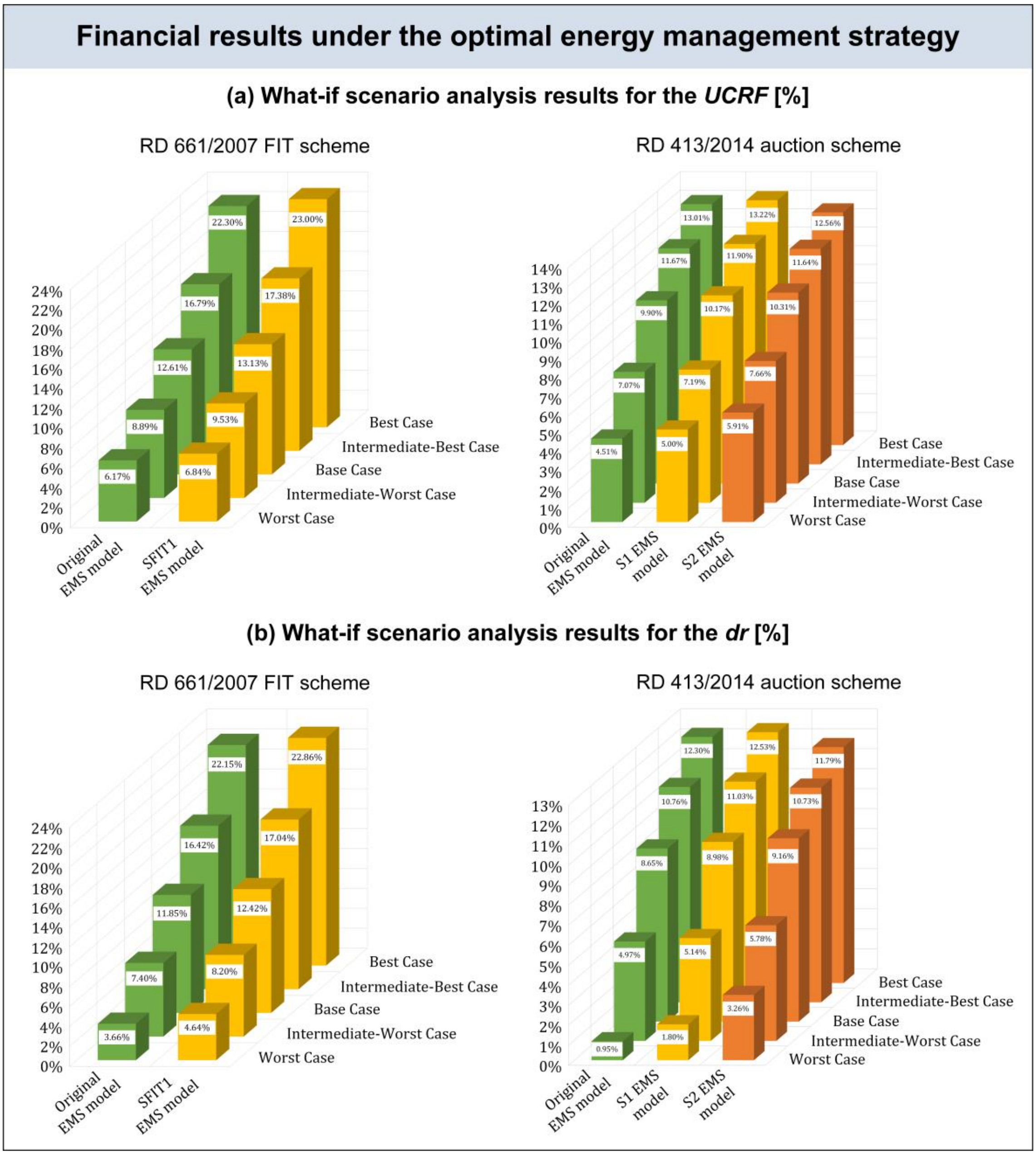


Fig. 15. Financial results under the optimal energy management strategy for the two remuneration schemes analysed, namely, RD 661/2007 FIT system and RD 413/2014 auction mechanism. What-if scenario analysis results for (a) the *UCRF*, (b) the *dr*. Source: self-elaboration.

On one side, the financial results obtained under the optimal energy management strategy for RD 661/2007 FIT scheme reveal an *UCRF* between 6.17% in the Worst Case and 22.30% in the Best Case, being 12.61% for the Base Case scenario (see Fig. 15a). In turn, it is expected a *dr* between 3.66% in the Worst Case and 22.15% in the Best Case, being 11.85% for the Base Case scenario (see Fig. 15b). On the other side, it is expected an *UCRF* between 4.51% in the Worst Case and 13.01% in the Best Case, being 9.90% for the Base Case scenario under RD 413/2014 auction mechanism (see Fig. 15a), while it is expected a *dr* between 0.95% in the Worst Case and 12.30% in the Best Case, being 8.65% for the Base Case scenario (see Fig. 15b).

In brief, on the one hand, the interval of errors obtained in the forecasting of the financial results under the optimal energy management strategy for the simplified model SFIT1 ranges from a minimum of +3% (Best Case) to a maximum of +11% (Worst Case) for *UCRF* and from a minimum of +3% (Best Case) to a maximum of +27% (Worst Case) for *dr*. On the other hand, the interval of errors obtained for the simplified models S1 and S2 varies, respectively, from a minimum of +2% (Best Case) to a maximum of +11% (Worst Case) and from a minimum of -3% (Best Case) to a maximum of +31% (Worst Case) for *UCRF*, while from a minimum of +2% (Best Case) to a maximum of +89% (Worst Case) and from a minimum of -4% (Best Case) to a maximum of +244% (Worst Case) for *dr*.

8. Discussion of results

The EMS model simplification here performed through the application of the sensitivity analysis mathematical technique has allowed, on the one hand, the identification of accessory input parameters representing a minor impact on the model output variable, i.e., the EBITDA, and therefore candidates to be neglected, which at the same time has enabled the reduction of the number of intermediate calculation variables as well as the number of equations of the EMS model, as shown in Tables 4 and 5 for RD 661/2007 FIT scheme and RD 413/2014 auction mechanism, respectively. On the other hand, the sensitivity simulation has also outlined those parameters especially relevant in the asset management. In particular, it has been noted the great impact of parameters such as the renewable power plant equivalent operating hours, the country-specific consumer price index or the facility fixed operating costs, on the asset management under the RD 661/2007 FIT scheme for the analysed case study. While parameters such as the variable operating costs or the degree of physical degradation of the facility, have an almost negligible impact on the outcomes under the FIT system. As for the RD 413/2014 auction mechanism, the sensitivity simulation conducted in the EMS model has highlighted the major effect of parameters such as the renewable power plant equivalent operating hours, the regulatory assigned reasonable profitability level, the average yield of the ten-year Spanish bonds, the electricity market price, the fixed operating costs or the tax on the remuneration of the generated energy, among others. While parameters such as the power plant variable operating costs, the facility degradation rate, the lower and the upper limits associated with the pool price or the economic tax on the produced electricity, among others, have practically no impact on the outcomes under the auction scheme. Ultimately, easing the judgement and decision-making of RE stakeholders when managing these energy assets as well as allowing them a better qualitative understanding of the whole system.

Therefore, the sensitivity analysis technique has been a useful tool to obtain two simplified model proposals, i.e., SFIT1 and SFIT2, for the FIT scheme and other two, i.e., S1 and S2, for the auction mechanism for the case study here analysed. On one side, the model proposal SFIT1 involves acting on almost 40% of the equations of the original EMS model and reducing the initial input parameters by 22%. Whereas the model proposal SFIT2 implies simplifying actions on 45% of the equations of the original EMS model and the elimination of more than 30% of the input parameters initially considered. According to the MC simulation output results, the model proposal SFIT1 has been validated and finally accepted as a simplified EMS model under the FIT scheme due to getting generalised errors below 5%, and therefore, lower than the 10% accuracy level threshold limit for selection applied, while the model proposal SFIT2 has not been accepted due to obtaining generalised errors around 15%. On the other side, as for the simplification proposals under the auction mechanism, the most conservative model proposal

S1 involves acting on almost 50% of the equations of the original EMS model and reducing the initial input parameters by 35%, while the less conservative model proposal S2 implies simplifying actions on more than 50% of the equations of the original EMS model and the elimination of more than 40% of the input parameters initially considered. Both simplified model proposals have been validated and finally accepted as simplified EMS models due to getting generalised errors in the Monte Carlo simulation output results below 5%.

Lastly, analysing the financial results obtained under the optimal energy management strategy for both economic mechanisms, it can be verified that the selected simplified EMS models, i.e., SFIT1 for RD 661/2007 FIT scheme and S1 and S2 for RD 413/2014 auction scheme, perform quite well compared to the original EMS models, as seen in Fig. 15. In general, the errors obtained are around ±5% with respect to the original models, with these simplified EMS models tending to slightly overestimate the expected financial results. Only under the extreme Worst Case scenario, the financial results deviate significantly more from the real expected value. As regards RD 413/2014 auction mechanism, the simplified EMS model S1 performs much better than S2.

9. Conclusions

This article has presented a novel methodology aimed at simplifying the EMS model, embedding the legal-economic constraints imposed by the country-specific support policies, of long operating life renewable assets under a high degree of uncertainty. In this regard, the most widely used remuneration schemes in the development of renewable energies worldwide, namely FIT and competitive auctions, have been considered in the present work by means of the Spanish CSP case study. Therefore, the simplifying methodology here provided is intended to be a useful tool to facilitate the optimal operating decision-making and management for renewable energy stakeholders.

The present simplification study has firstly revealed the importance of having a well-modelled regulatory framework when conducting the operation and management of these renewable power plants. In this regard, the implementation of the sensitivity analysis on the EMS model has allowed a detailed understanding thereof, identifying both the accessory input parameters representing a minor impact on the EBITDA output variable, as well as those parameters especially relevant in the asset management. Therefore, allowing the corresponding EMS model simplification based on the knowledge acquired.

In short, the validity of the achieved simplified models, checked through the Monte Carlo simulation, by applying the simplifying methodology here presented on the Spanish CSP case study demonstrates the suitability and usefulness of the proposed methodology, providing a touch of quality in the long-term judgement and decision-making of the stakeholders when optimally managing renewable energy facilities under any type of remuneration scheme. Specifically, it has been possible to obtain the simplified model SFIT1 under the FIT scheme and the simplified models S1 and S2 under the auction scheme, obtaining in all of them generalized errors in the Monte Carlo simulation results below 5% with respect to their corresponding original model.

The obtained simplified models provide a similar characterization to that of the original EMS model, but with fewer input parameters and intermediate calculation variables, as well as equations, resulting in an analysis in the mid and long term less burdensome for developers of the renewable sector. In this vein, as it contributes in the model linearization and allows a more considerable simplification of the computing process, it is expected that these simplified models may be a useful tool to optimise and evaluate the prospective operating and management results of these assets. By means of obtaining the simplified EMS models the optimal energy management strategy for these long operating life assets has been substantially simplified. Especially, in the case of the auction mechanism where no intuitive approach could be easily obtained, the resulting methodology has been proved to be successful to provide clear guidelines regarding the optimal long-term operation strategy on the revenue and costs of these renewable assets in order to optimize the available resources as well as the profitability of electricity generation.

Even so, the uncertainty on the energy assets remains and may affect its prospective financial results, although to a reduced rate, under the determined optimal energy management strategy. In the same way, the achieved simplified models for both economic mechanisms perform successfully compared to the original EMS model, obtaining generalised errors around 5% in the financial results calculated from the what-if scenario analysis conducted for the facility useful life.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex A. EMS model formulation for RD 661/2007 FIT scheme

As shown in Table A.1, where the formulation of the CSPP remuneration model under RD 661/2007 FIT scheme is defined, the yearly $Revenue\_{_i}$ is calculated as the product of the FIT remuneration ($R\_FIT\_{_i}$) by the total energy produced ($E\_{_i}$), as seen in Eq. (A.1).

Table A.1
Mathematical formulation of the CSPP remuneration model under RD 661/2007 FIT scheme. Source: self-elaboration.

Equation	Eq. Nr.

$$Revenue_{\_i} = R\_FIT_{\_i} \cdot E_{\_i} \tag{A.1}$$

$$R\_FIT_{\_i} = FIT_{\_i} \cdot (1 + RR_{\_i})^{i-(a+1)}, \quad i \geq a+1 \tag{A.2}$$

$$RR_{\_i} = IPC - r_{\_i} \tag{A.3}$$

$$E_{\_i} = P_{\_n} \cdot Nh\_inst_{\_i} \tag{A.4}$$

$$Nh\_inst_{\_i} = Nh\_inst_{\_a+1} \cdot \left[1 - K_{\_R} \cdot \left(i - (a+1)\right)\right], \quad i \geq a+1 \tag{A.5}$$

The $R\_FIT_{\_i}$ is updated annually as seen in Eq. (A.2), according to the updating factor $RR_{\_i}$ obtained as the difference between the consumer price index (*IPC*) and a curtailment rate defined by the Government ($r_{\_i}$) (see Eq. (A.3)). In turn, $E_{\_i}$ depends on the CSPP nominal power ($P_{\_n}$) and its annual number of equivalent operating hours ($Nh\_inst_{\_i}$), and it is computed as shown in Eq. (A.4). Likewise, as observed in Eq. (A.5), the CSPP $Nh\_inst_{\_i}$ is defined as a decreasing function depending on the year when the CSP facility acquired the operating permit (*a*), its initial number of equivalent operating hours within the year *a+1* ($Nh\_inst_{\_a+1}$) and the yearly degradation rate ($K_{\_R}$).

Regarding the formulation of the yearly operating cost model (see Table A.2), the CSPP $Operating\_Cost_{\_i}$ is obtained as the sum of the fixed ($Fixed\_OMC_{\_i}$) and variable ($Variable\_OMC_{\_i}$) operating and maintenance costs, as shown in Eq. (A.6).

Table A.2
Mathematical formulation of the CSPP operating cost model under RD 661/2007 FIT mechanism. Source: self-elaboration.

Equation	Eq. Nr.
$Operating\_Cost_{\_i} = Fixed\_OMC_{\_i} + Variable\_OMC_{\_i}$	(A.6)
$Fixed\_OMC_{\_i} = F\_OMC_{\_i} \cdot P_{\_n}$	(A.7)
$F\_OMC_{\_i} = F\_OMC_{\_a+1} \cdot (1 + IPC)^{i-(a+1)}$	(A.8)
$Variable\_OMC_{\_i} = V\_OMC_{\_i} \cdot E_{\_i}$	(A.9)

$$V\_OMC_{\_i} = V\_OMC_{\_a+1} \cdot (1 + IPC)^{i-(a+1)} \quad \text{(A.10)}$$

The *Fixed_OMC*$_{\_i}$ is directly proportional to *P*$_{\_n}$ as seen in Eq. (A.7), while the *Variable_OMC*$_{\_i}$ is proportional to *E*$_{\_i}$ as observed in Eq. (A.9). In both cases, as denoted in Eqs. (A.8) and (A.10), these costs are annually updated according to the *IPC*.

Annex B. EMS model formulation for RD 413/2014 auction mechanism

The CSPP annual remuneration model depicted in Table B.1 corresponds to RD 413/2014 auction mechanism. The *Revenue*$_{\_i}$ is computed as the sum of the market revenue (*Market_Revenue*$_{\_i}$) and the specific remuneration revenue (*SR_Revenue*$_{\_i}$), as seen in Eq. (B.1).

Table B.1
Mathematical formulation of the CSPP remuneration model under RD 413/2014 auction mechanism. Source: self-elaboration based on de la Hoz et al. (2018).

Equation	Eq. Nr.
$Revenue_{\_i} = Market\_Revenue_{\_i} + SR\_Revenue_{\_i}$	(B.1)
$Market\_Revenue_{\_i} = E_{\_i} \cdot Pm_{\_i}$	(B.2)
$E_{\_i} = P_{\_n} \cdot Nh\_inst_{\_i}$	(B.3)
$Nh\_inst_{\_i} = Nh\_inst_{\_a+1} \cdot \left[1 - K_{\_R} \cdot \left(i - (a+1)\right)\right], \quad i \geq a+1$	(B.4)
$SR\_Revenue_{\_i} = (Op\_R_{\_i} + Inv\_R_{\_i}) \cdot d_{\_i}$	(B.5)
$d_{\_i} = \begin{cases} 1 & Nh\_inst_{\_i} > Nh\_min_{\_i} \\ \dfrac{Nh\_inst_{\_i} - Uf_{\_i}}{Nh\_min_{\_i} - Uf_{\_i}} & Uf_{\_i} \leq Nh\_inst_{\_i} \leq Nh\_min_{\_i} \\ 0 & Uf_{\_i} > Nh\_inst_{\_i} \end{cases}$	(B.6)
$Op\_R_{\_i} = \begin{cases} E_{\_i} \cdot Ro_{\_i}, & E_{\_i} \leq E\_max_{\_i} \\ E\_max_{\_i} \cdot Ro_{\_i}, & E_{\_i} > E\_max_{\_i} \end{cases}$	(B.7)

$$E\_max\_i = P\_n \cdot Nh\_max\_{(R_o)i} \tag{B.8}$$

$$Ro\_i = C\_Eexpf\_i - Pmf\_i \tag{B.9}$$

$$C\_Eexpf\_i = C\_Eexpf\_{2014} \cdot (1 + \Delta\_Std\_Cost)^{(i-2014)} \tag{B.10}$$

$$Inv\_R\_i = P\_n \cdot Rinv\_{j,a} \tag{B.11}$$

$$Rinv\_{j,a} = \begin{cases} C\_{j,a} \cdot VNA\_{j,a} \cdot K\_j, & PT\_IRR\_i \leq LR \\ 0, & PT\_IRR\_i > LR \end{cases} \tag{B.12}$$

$$C\_{j,a} = \frac{VNA\_{j,a} - \sum_{i=p}^{a+VU} \dfrac{(Ingf\_i - Cexpf\_i)}{(1+t\_j)^{i-p+1}}}{VNA\_{j,a}} \tag{B.13}$$

$$Ingf\_i = (Pmf\_i + Ro\_i) \cdot Nh\_{i,j} \tag{B.14}$$

$$Cexpf\_i = C\_Eexpf\_i \cdot Nh\_{i,j} \tag{B.15}$$

$$Nh\_{i,j} = Nh\_{2014} \cdot (1 - K\_{RR})^{(i-2014)} \tag{B.16}$$

$$VNA\_{j,a} = \begin{cases} VI\_a \cdot (1+t\_j)^{p-a-1} - \sum_{i=a+1}^{p-1} (Ing\_i - Cexp\_i) \cdot (1+t\_j)^{p-i-1}, & j = 1 \\ VNA\_{j-1,a} \cdot (1+t\_{j-1})^{sm} - \sum_{i=p-sm}^{p-1} \left(Ingf\_{i,j-1} - Cexpf\_{i,j-1} - Vajdm\_{i,j-1}\right) \cdot (1+t\_{j-1})^{p-i-1}, & j > 1 \end{cases} \tag{B.17}$$

$$Ing\_i = Pm\_e\_i \cdot Nh\_e\_i \tag{B.18}$$

$$Cexp\_i = C\_Eexp\_e\_i \cdot Nh\_e\_i \tag{B.19}$$

$$Vajdm_{\_i,j} = \begin{cases} Nh_{\_i,j} \cdot 0{,}5 \cdot \left(LS1_{\_i,j} - LS2_{\_i,j}\right) + Nh_{\_i,j} \cdot \left(LS2_{\_i,j} - Pm_{\_i}\right), & Pm_{\_i} > LS2_{\_i,j} \\ Nh_{\_i,j} \cdot 0{,}5 \cdot \left(LS1_{\_i,j} - Pm_{\_i}\right), & LS1_{\_i,j} \leq Pm_{\_i} \leq LS2_{\_i,j} \\ 0, & LI1_{\_i,j} \leq Pm_{\_i} \leq LS1_{\_i,j} \\ Nh_{\_i,j} \cdot 0{,}5 \cdot \left(LI1_{\_i,j} - Pm_{\_i}\right), & LI2_{\_i,j} \leq Pm_{\_i} \leq LI1_{\_i,j} \\ Nh_{\_i,j} \cdot 0{,}5 \cdot \left(LI1_{\_i,j} - LI2_{\_i,j}\right) + Nh_{\_i,j} \cdot \left(LI2_{\_i,j} - Pm_{\_i}\right), & Pm_{\_i} < LI2_{\_i,j} \end{cases} \quad \text{(B.20)}$$

$$t_{\_j} = SB_{\_j} + \Delta t_{\_j} \quad \text{(B.21)}$$

$$K_{\_j} = \frac{t_{\_j} \cdot \left(1 + t_{\_j}\right)^{VR_{\_j}}}{\left(1 + t_{\_j}\right)^{VR_{\_j}} - 1} \quad \text{(B.22)}$$

On one side, the *Market_Revenue*$_{\_i}$ is computed as the annual average electricity market price per unit of produced energy (*Pm*$_{\_i}$) by *E*$_{\_i}$ (see Eq. (B.2)). Note that, in the same way as under RD 661/2007 FIT scheme, *E*$_{\_i}$ depends on *P*$_{\_n}$ and *Nh_inst*$_{\_i}$, as shown in Eq. (B.3). Similarly, *Nh_inst*$_{\_i}$ is defined as a decreasing function depending on three parameters, i.e., *Nh_inst*$_{\_a+1}$, *K*$_{\_R}$ and *a*, as observed in Eq. (B.4).

On the other side, the yearly *SR_Revenue*$_{\_i}$ (see Eq. (B.5)) is obtained as the sum of the remuneration for the operation (*Op_R*$_{\_i}$) and the remuneration for the investment (*Inv_R*$_{\_i}$), multiplied by a weighting factor *d*$_{\_i}$. This weighting factor corrects the *SR_Revenue*$_{\_i}$ according to whether *Nh_inst*$_{\_i}$ is above or below two regulatory assigned threshold values (*Nh_min*$_{\_i}$ and *Uf*$_{\_i}$), as denoted in Eq. (B.6). Note that the *SR_Revenue*$_{\_i}$ is received during the CSPP useful life (*VU*). Thereafter, just the *Market_Revenue*$_{\_i}$ will be received. As for the *Op_R*$_{\_i}$, it is computed as the annual remuneration for the operation per unit of produced energy (*Ro*$_{\_i}$) multiplied by *E*$_{\_i}$ (see Eq. (B.7)). Likewise, it is aimed at offsetting the yearly standard operating cost per unit of produced energy assessed for an "efficient and well-managed" CSP facility (*C_Eexpf*$_{\_i}$) that cannot be regained with the estimated future market price per unit of produced energy (*Pmf*$_{\_i}$), as denoted in Eq. (B.9). However, the *E*$_{\_i}$ opting to receive the *Op_R*$_{\_i}$ has a maximum threshold (*E_max*$_{\_i}$) proportional to the regulatory assigned peak value of *Nh_inst*$_{\_i}$ entitled to receive this remuneration for the operation (*Nh_max*$_{\_(Ro)i}$) (see Eqs. (B.7) and (B.8)). It is worth mentioning that, as seen in Eq. (B.10), the *C_Eexpf*$_{\_i}$ is defined as a function depending on the yearly increase in standard operating cost per unit of generated energy (*Δ_Std_Cost*). Regarding the *Inv_R*$_{\_i}$ (see Eq. (B.11)), it is calculated as the yearly remuneration for the investment per unit of installed power within a three-year regulatory half-period *j* of a CSP facility getting the operating permit in a year *a* (*Rinv*$_{\_j,a}$) multiplied by *P*$_{\_n}$. In turn, *Rinv*$_{\_j,a}$ depends on three variables which remain constant within *j* (see Eq. (B.12)), specifically, a per unit adjustment coefficient representing the investment cost that cannot be regained with the market revenue (*C*$_{\_j,a}$) calculated as shown in Eqs. (B.13)-(B.16), the net value of the facility per unit of installed power (*VNA*$_{\_j,a}$) computed as expressed in Eqs. (B.17)-(B.21), and a capital recovery factor (*K*$_{\_j}$) obtained as shown in Eq. (B.22). Note that, as observed in Eq. (B.12), *Rinv*$_{\_j,a}$ is only perceived by the CSPP if the annual internal rate of return before taxes (*PT_IRR*$_{\_i}$) does not exceed the reasonable profitability threshold established by the Spanish Government (*LR*).

In this case, it is important to highlight that all the regulatory assigned parameters, with the exception of the standard value of the initial investment per unit of installed power (VI_a) and the VU, can be reviewed and updated at the end of each six-year regulatory period (or each three-year regulatory half-period j) by the Spanish Government.

Regarding the CSPP annual operating cost model under RD 413/2014 economic regime (see Table B.2), the $Operating\_Cost\_i$ is obtained as the sum of the fixed ($Fixed\_OMC\_i$) and variable ($Variable\_OMC\_i$) operating and maintenance costs, and the annual electricity taxes, i.e., the tax on the generated energy ($ETax\_Cost\_i$) and the tax on the remuneration of the generated energy ($RTax\_Cost\_i$), as shown in Eq. (B.23).

Table B.2
Mathematical formulation of the CSPP operating cost model under RD 413/2014 economic regime. Source: self-elaboration.

Equation	Eq. Nr.
$Operating\_Cost_{\_i} = Fixed\_OMC_{\_i} + Variable\_OMC_{\_i} + ETax\_Cost_{\_i} + RTax\_Cost_{\_i}$	(B.23)
$Fixed\_OMC_{\_i} = F\_OMC_{\_i} \cdot P_{\_n}$	(B.24)
$F\_OMC_{\_i} = F\_OMC_{\_a+1} \cdot (1 + IPC)^{i-(a+1)}$	(B.25)
$Variable\_OMC_{\_i} = V\_OMC_{\_i} \cdot E_{\_i}$	(B.26)
$V\_OMC_{\_i} = V\_OMC_{\_a+1} \cdot (1 + IPC)^{i-(a+1)}$	(B.27)
$ETax\_Cost_{\_i} = Tax\_E \cdot E_{\_i}, \quad 2011 \leq i \leq a + VU$	(B.28)
$RTax\_Cost_{\_i} = Tax\_R \cdot Revenue_{\_i}, \quad 2013 \leq i \leq a + VU$	(B.29)

The $Fixed\_OMC\_i$ is directly proportional to P_n as seen in Eq. (B.24), while the $Variable\_OMC\_i$ is proportional to E_i as observed in Eq. (B.26). In both cases, as denoted in Eqs. (B.25) and (B.27), these costs are annually updated according to the IPC. Finally, the $ETax\_Cost\_i$ is calculated as the product of E_i by the value of the tax on the generated energy per unit of energy (Tax_E) established in a regulatory manner and applied from the year 2011 onwards (see Eq. (B.28)). Whereas the $RTax\_Cost\_i$ is calculated as the product of the $Revenue\_i$ by the value of the tax on the remuneration (Tax_R) regulatorily set and applied from the year 2013 on (see Eq. (B.29)).

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Nomenclature

Acronyms

CSP: Concentrating solar power

CSPP: Concentrating solar power plant

EBITDA: Earnings before interest, taxes, depreciation and amortization

EMS: Energy management system

EU: European Union

FIT: Feed-in tariffs

IQR: Interquartile range

MC: Monte Carlo

NPV: Net present value

PDF: Probability density function

PV: Photovoltaic

RD: Royal Decree

RE: Renewable energy

RES: Renewable energy sources

RPS: Renewable portfolio standards

SCSPS: Spanish concentrating solar power sector

TGC: Tradable green certificates

Variables and parameters

a: year in which the operating permit of a CSP facility is obtained

$C\_{j,a}$: coefficient signifying the investment cost of a CSP facility getting the operating permit in the year a that cannot be regained with the market revenue within *j*

$C\_Eexp\_e\_{i}$: standard operating cost per unit of produced energy in the year *i* under the former Spanish legal-economic frameworks [€/MWh]

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

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

$Cexp\_{i}$: standard operating cost per unit of installed power for a year *i* under the former Spanish legal-economic frameworks [€/MW]

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

d_{i}: weighting factor decreasing $SR\_Revenue\_{i}$ in accordance with Nh_inst_{i}

$DATA$: input parameters of the first group for an EMS model

dr: discounted rate associated with the *UCRF* of an energy asset [%]

E_{i}: total energy produced within the year *i* [MWh]

$E\_{i,d,h}$: total energy produced within an hour *h* on a particular day *d* of the year *i* [MWh]

E_max_{i}: peak value of E_{i} eligible for receiving the Ro_{i} [MWh]

$EBITDA$: cumulative updated $EBITDA\_{i}$ [€]

$EBITDA\_{BS}$: base scenario result for the *EBITDA* of the CSPP [€]

$EBITDA\_{i}$: earnings before interest, taxes, depreciation and amortization of the CSPP in the year *i* [€]

$EBITDA\_{i,d,h}$: earnings before interest, taxes, depreciation and amortization of the CSPP within an hour *h* on a particular day *d* of the year *i* [€]

$EBITDA\_Original\_EMS_{ns}$: *EBITDA* for each MC sample under the any remuneration scheme of the original EMS model [€]

$EBITDA\_Relative\_Error(RD\ 413/2014)_{ns}$: *EBITDA* relative error for each MC sample under RD 413/2014 [%]

$EBITDA\_Relative\_Error(RD\ 661/2007)_{ns}$: *EBITDA* relative error for each MC sample under RD 661/2007 [%]

$EBITDA\_Simplified\_EMS_{ns}$: *EBITDA* for each MC sample under the any remuneration scheme of the simplified EMS models [€]

$ETax\_Cost\_{i}$: tax on the generated energy in the year *i* [€]

$ETax\_Cost\_{i,d,h}$: tax on the generated energy within an hour *h* on a particular day *d* of the year *i* [€]

F_OMC_{a+1}: fixed operating cost within the year $a+1$ per unit of installed power [€/kW]

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

$F\_OMC\_{i,d,h}$: fixed operating cost within an hour *h* on a particular day *d* of the year *i* per unit of installed power [€/kW]

FCR: fixed charge rate of an energy asset [%]

FIT_{a}: feed-in tariff of a CSPP getting the operating permit in the year a under RD 661/2007 [€/MWh]

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

$Fixed\_OMC\_{i}$: fixed operating cost in the year *i* [€]

$Fixed\_OMC\_{i,d,h}$: fixed operating cost within an hour *h* on a particular day *d* of the year *i* [€]

IC: investment cost of an energy asset [€]

Ing_{i}: standard revenues per unit of installed power for a year *i* under the former Spanish legal-economic frameworks [€/MW]

$Ingf\_{i}$: standard revenues per unit of installed power within the year i under RD 413/2014 [€/MW]

Inv_R_{i}: remuneration for the investment in the year *i* [€]

$Inv\_R\_{i,d,h}$: remuneration for the investment within an hour *h* on a particular day *d* of the year *i* [€]

IPC: consumer price index [%]

j: three-year half-period

K_j: capital recovery factor

K_R: physical annual degradation rate [%]

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

LR: reasonable profitability [%]

$LI1\_{i,j}$, $LI2\_{i,j}$: lower limits for the computation of $Vajdm\_{i,j}$ [€/MWh]

$LS1\_{i,j}$, $LS2\_{i,j}$: upper limits for the computation of $Vajdm\_{i,j}$ [€/MWh]

$Market\_Revenue\_i$: market revenue received in the year *i* [€]

$Market\_Revenue\_{i,d,h}$: market revenue received within an hour *h* on a particular day *d* of the year *i* [€]

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

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

Nh_e_i: standard equivalent operating hours within the year i under the former Spanish legal-economic frameworks [h]

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

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

$Nh\_inst\_max\_i$: the highest value of real equivalent operating hours within the year i under any regulatory framework [h]

$Nh\_max\_{(Ro)i}$: highest value of Nh_inst_i eligible for receiving the Ro_i [h]

Nh_min_i: lowest value of Nh_inst_i that does not imply a cutback of $SR\_Revenue\_i$ [h]

ns: number of MC sample

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

$Operating\_Cost\_i$: total operating cost for running the CSP facility in the year *i* [€]

p: first complete year of j

P_n: nominal power [MW]

Pc: annual cost of an energy asset as a percentage of *IC* [%]

Pm_{i}: average electricity market price per unit of produced energy in the year *i* [€/MWh]

$Pm\_{i,d,h}$: average electricity market price per unit of produced energy within an hour *h* on a particular day *d* of the year *i* [€/MWh]

Pm_e_{i}: revenue per unit of produced energy in the year *i* under the former Spanish legal-economic frameworks [€/MWh]

Pmf_{i}: future estimated average market price per unit of produced energy for the year *i* [€/MWh]

P_{sk}: kth input parameter of the second group for an EMS model

P_{sk_BS}: base scenario value for each P_{sk}

PT_IRR_{i}: pre-tax internal rate of return up to the year *i* [%]

r_{i}: curtailment for *IPC* in the year *i* under RD 661/2007 [%]

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

$R\_FIT\_{i,d,h}$: feed-in tariff remuneration within an hour *h* on a particular day *d* of the year *i* for a CSPP under RD 661/2007 [€/MWh]

$Revenue\_{i}$: total income received in the year *i* [€]

$Rinv\_{j,a}$: remuneration for the investment per unit of installed power in a year *i* within *j* of a CSP facility acquiring the operating permit in the year *a* [€/MW]

Ro_{i}: remuneration for the operation per unit of produced energy in the year *i* [€/MWh]

$Ro\_{i,d,h}$: remuneration for the operation per unit of produced energy within an hour *h* on a particular day *d* of the year *i* [€/MWh]

RR_{i}: difference between *IPC* and r_{i} in the year *i* under RD 661/2007 [%]

$RTax\_Cost\_{i}$: tax on the remuneration of the generated energy in the year *i* [€]

$RTax\_Cost\_{i,d,h}$: tax on the remuneration of the generated energy within an hour *h* on a particular day *d* of the year *i* [€]

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

sm: number of years of *j*

$SR\_Revenue\_{i}$: specific remuneration revenue received in the year *i* [€]

$SR\_Revenue\_{i,d,h}$: specific remuneration revenue received within an hour *h* on a particular day *d* of the year *i* [€]

t_{j}: per unit discount rate within *j* corresponding to the reasonable profitability

t_{ur}: fixed update rate [%]

Tax_E: tax on the generated energy per unit of energy [€/MWh]

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

TSR: total stream of repayment of an energy asset [€]

$UCRF$: uniform capital recovery factor of an energy asset [%]

Uf_{i}: threshold of Nh_inst_{i} for receiving $SR\_Revenue\_{i}$ [h]

ULT: useful lifetime of an energy asset [years]

V_OMC_{a+1}: variable operating and maintenance cost within the year $a+1$ per unit of produced energy [€/MWh]

V_OMC_{i}: variable operating and maintenance cost in the year *i* per unit of produced energy [€/MWh]

$V\_OMC\_{i,d,h}$: variable operating and maintenance cost within an hour *h* on a particular day *d* of the year *i* per unit of produced energy [€/MWh]

$Vajdm\_{i,j}$: coefficient adjusting the deviations of Pm_{i} from Pmf_{i} [€/MW]

$Variable\_OMC\_{i}$: variable operating and maintenance cost in the year *i* [€]

$Variable\_OMC\_{i,d,h}$: variable operating and maintenance cost within an hour *h* on a particular day *d* of the year *i* [€]

VI_{a}: standard value of the initial CSP facility 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 CSP plant acquiring the operating permit in the year a [€/MW]

VR_{j}: unexpired number of years at the beginning of *j* to the end of the CSP facility useful life [years]

VU: regulatory useful life [years]

x_k: lower limit for the variation of each P_{sk} in the sensitivity analysis simulation

y_k: upper limit for the variation of each P_{sk} in the sensitivity analysis simulation

$y\_{j,d,h}$: binary variable which is activated ($y\_{i,d,h}$ =1) if it is decided to operate the power plant within an hour *h* on a particular day *d* of the year *i* under any regulatory framework

Δ_Std_Cost: annual increment in standard operating cost per unit of produced energy under RD 413/2014 [%]

ΔT: time step of 1 hour [h]

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

Figure list

Table list

Table 2
Values of the regulatory parameters for a CSP asset under the auction mechanism defined by RD 413/2014. Source: self-elaboration based on Orden ETU/130/2017 (2017); Orden IET/1045/2014 (2014) and RD 413/2014 (2014).

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-00604	2012	25	4,576,096	1	192,265	410,391	411,681	956	2040	2028	245	1224	1217	143	714	710

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]
2012	–	–	–	–	–	–	–	–	–	–	–
2013	296.44	105.10	52.35	91.85	917	956	–	–	–	–	39.495
2014	–	–	49.21	88.90	–	2040	56.21	52.21	44.21	40.21	39.694
2015	–	–	50.55	89.64	–	2036	57.52	53.52	45.52	41.52	39.090
2016	–	–	50.78	90.52	–	2032	57.75	53.75	45.75	41.75	39.745
2017	–	–	44.96	91.43	–	2028	49.81	46.33	39.35	35.87	46.474
2018	–	–	43.60	92.31	–	2024	48.30	44.92	38.16	34.78	48.711
2019	–	–	43.94	93.19	–	2020	48.68	45.28	38.46	35.06	49.248
2020	–	–	54.57	94.08	–	2016	60	56	48	44	–