Energy Economics 139 (2024) 107861

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Assessing the value and risk of renewable PPAs

Julio Pombo-Romero [a,*], Oliver Rúas-Barrosa [a,b], Carlos Vázquez [b]

[a] Instituto de Energía Solar - Universidad Politécnica de Madrid, 28031, Madrid, Spain
[b] Department of Mathematics, Faculty of Informatics and CITIC, Campus Elviña s/n, 15071-A Coruña, Spain

ARTICLE INFO

JEL classification:
C02
C22
C63
G12
G13
Q41

Keywords:
Power purchase agreements (PPAs)
Pricing
Credit risk
Renewable energy
Levelized cost of energy (LCOE)

ABSTRACT

Renewable Energy Power Purchase Agreements (RE PPAs) are considered to be a key tool in order to foster RE deployment, as they allow for the reduction of uncertainty for all parties as well as facilitating access to the long term finance required for such projects. Nevertheless, RE PPA adoption is hampered by a number of barriers, including the high level of guarantees demanded from offtakers, a problem which is related to the shortcomings of existing assessment methodologies, in particular, determining the credit risk of the PPA itself. In this work, we propose an RE PPA assessment model focused on the main drivers of value and risk for the offtaker which are cost and volatility reductions, compared to the electricity market. By identifying and valuing the options for the offtaker embedded in the PPA, it is possible to determine the default probability at any given time and the expected loss for the producer, thus allowing for the estimation of the amount of guarantees needed to hedge the credit risk.

1. Introduction

Renewable Energy (RE) projects require relatively high CAPital EXpenditure (CAPEX) in relation to their OPerational EXpenditure (OPEX), as they do not consume fuel. Most RE CAPEX must be paid for before the beginning of operations and are paid back throughout relatively long periods, which can last 30 years or more. As a result, RE stakeholders, including investors and energy consumers, must perceive a sufficient level of predictability and stability in relation to the technical and economic performance of the projects. In this context, Power Purchase Agreements (PPAs) are effective tools to reduce the uncertainties of RE projects and therefore facilitate their expansion (Baringa Partners LLC, 2022). A PPA is defined as a bilateral contract between an electricity generator (the producer) and an electricity consumer (the offtaker) whereby the offtaker agrees to purchase a certain amount of electricity from the producer at predetermined times and prices. PPAs can take different forms in order to adapt to a variety of particularities of the deal: the type of counterparties, the origin of the energy, the settling mechanisms and others (Hundt et al., 2021). Usually, PPAs are classified according to whether or not there is a physical delivery and regarding the amount of electricity to be supplied (Gabrielli et al., 2022; Source, 2020).

In the case of RE PPAs, the producer designs, builds and operates an RE system connected to the offtaker's consumption centre in order to deliver the settled amount of electricity. Once the RE system enters into operation, the offtaker is periodically billed for the electricity as per the terms agreed in the PPA. As PPA producers are entities specialized in designing, building and operating RE systems, they are better suited to dealing with such activities than the offtakers. Furthermore, the PPA ensures long term commitment to the project for both parties, thus facilitating interests alignment. The existence of a PPA also has an impact on the economic assessment of RE projects, for several reasons, such as Bruck and Sandborn (2021):

1. The cost of capital is lower for both the producers and the funding parties due to lower uncertainty regarding the revenue of the project since prices, quantities, costs and time of delivery are known in advance.
2. A PPA is a transferable contract containing a payment obligation for the offtaker, so it can be used as a collateral for financial providers. This makes RE projects more bankable and facilitates further reductions in the cost of capital.
3. A significant part of the project risk is transferred from the offtaker to the producer, who is used to manage them.

Nevertheless, despite the aforementioned advantages, RE PPAs are also relatively new and complex instruments, so that there exist a lack of standardization and track-records regarding their performance

* Corresponding author.
E-mail addresses: julio.pombo@upm.es (J. Pombo-Romero), oliver.ruas@udc.es (O. Rúas-Barrosa), carlosv@udc.es (C. Vázquez).

https://doi.org/10.1016/j.eneco.2024.107861
Received 4 April 2023; Received in revised form 3 July 2024; Accepted 21 August 2024
Available online 30 August 2024

(Hundt et al., 2021). As a result, many of the specific economic risks associated to RE PPA, including credit and obsolescence risk, are only partially understood and, therefore, difficult to assess. The limitations of existing valuation methodologies and risk management tools to deal with such uncertainties involve negative consequences for the accessibility and funding costs for RE projects, thus limiting their bankability and the use of project finance solutions and preventing RE PPAs from being considered as an asset class on their own by investors and financial intermediaries (Baker McKenzie, 2015).

Summing up, the relevance of assessing the value and risk of PPAs is of utmost importance mainly to:

- Facilitate RE projects access to larger pools of affordable funds by means of RE PPAs, for example coming from institutional investors.
- Support investors and offtakers for taking more suitable decisions about entering into RE PPAs.
- Estimate the cost of capital associated to RE PPAs.
- Design efficient supporting financial tools to reach decarbonization targets.

One of the difficulties with assessing the value and the risk of RE PPAs arises from the fact that they deliver value for both the offtaker and the producer in different ways. On one hand, for the producer, an RE PPA essentially represents a capital investment which can be valued on the basis of a techno-economic assessment. In this regard, the value for the producer depends on the difference between the revenue from selling electricity to the offtaker at the agreed price (P_{PPA}) and the cost of producing such electricity, usually referred to as the Levelized Cost of Energy (LCOE). On the other hand, the value for the offtaker of the PPA is not related to the production cost of electricity. Instead, for a given P_{PPA}, the value of the RE PPA for the offtaker will depend on the cost and volatility of the electricity in the market, which is the alternative to meeting their energy requirements. Thus, if the price P_{PPA} is lower than the cost of the energy in the electricity market (P_t) at the requested times, the offtaker will save money, which is valuable. Furthermore, as P_{PPA} is usually fixed or indexed to inflation, the RE PPA reduces the volatility of the price of the electricity for the offtaker in relation to P_t, so that the risk of the expected net revenue is lower and, consequently, its value is higher. Thus, the more volatile P_t is, the more valuable the PPA is for the offtaker.

In practice, most RE PPA valuations are carried out from the producers' perspective, because they are the ones who take the investment decision. Then, the credit risk of the RE PPA is assessed by the producer and his/her financial partners as part of the financial appraisal previous to the investment. This is usually done by focusing on the credit rating of the offtaker and his/her capability to provide collateral to fully hedge the investment requirements. The resulting valuations pay limited or no attention to the main driver of credit risk of the project itself, which is the probability that the value of the RE PPA eventually becomes negative for the offtaker, and effectively assumes that it is always the case. The described approach to RE PPA risk assessment results in excessively high credit requirements for potential offtakers and a lack of tailored financial instruments and hedging strategies for potential producers and investors. The aforementioned problems have been identified as significant barriers to RE PPA expansion and competitiveness (Baringa Partners LLC, 2022).

In order to contribute to the understanding of the previously described situation, in this article we propose an RE PPA valuation model that also allows for the assessment of the credit risk of the project itself, which is independent of the credit rating of the offtaker. A contingent claim analysis of an uncollateralized RE PPA enables the identification and valuation of the options embedded for the offtaker as well as the estimation of the default probability at any time. Given this latter measurement, the expected loss may be computed and, consequently, the amount of collateral that must be demanded from the offtaker to hedge such losses can be obtained. This is a significant contribution to the existing valuation and risk assessment methodologies as it allows for a better understanding of the relationships between electricity markets, RE PPA value for offtakers and financial appraisal of the projects for producers and lenders. In next paragraphs of this introduction, we carry out a literature review on the topic of valuation and risk assessment of PPAs.

A PPA can be understood as a complex electricity derivative which provides an insurance against rising electricity prices as well as consumption/generation requirements. Indeed, some research on this topic identified PPAs as an electricity derivative, more precisely as an electricity forward contract with time-continuous delivery (Mäntyvaara, 2022). Due to the price hedging feature of PPAs and scheduled deliveries of electricity, some similarities might be found regarding swing options. A swing option allows the holder to exercise the involved right a number of times thoughout a period of time with a penalty between two consecutive exercise times and with a penalty on the volume exercised both at each exercise time and for the remaining volume (Kluge, 2006). Then, the value of the swing option comes from the flexibility provided that the penalty time enables and the option to acquire more units of the commodity (Dahlgren, 2005). Nevertheless, unlike swing options, which allows the holder the possibility so as not to exercise all the rights (Calvo-Garrido et al., 2019), PPAs do not offer the possibility of not exercising the embedded options. Furthermore, depending on the considered type of PPA, the electricity to be delivered depends on the renewable generation (which in turn depends on weather conditions, for example) and the demand profile, so that a mismatching may arise. Actually, these differences between standard electricity derivatives and a PPA introduce several sources of risk: price, volume, shape and credit risk, outlined in Gabrielli et al. (2022) and Source (2020). It should be noted that PPAs regardless of being an electricity derivative they are suited to meeting sustainability targets (Mäntyvaara, 2022; Ghiassi-Farrokhfal et al., 2021), which is not the main issue of swing options (and other electricity derivatives). An additional classification of PPAs might be introduced depending on whether or not they include Renewable Energy Certificates (also known as Guarantees of Origin depending on the country) (Bachus, 2023).

PPA assessments are mainly conducted by producers in order to determine the price of the electricity that can be offered to prospective offtakers. In the case of RE PPAs, the price of the PPA is usually established on the basis of the LCOE of the project (Mendicino et al., 2019). In order to calculate the LCOE, the producer has to consider a suitable RE system and estimate the necessary CAPEX and OPEX to produce and deliver the electricity to the offtaker's consumption centre at each time during the lifespan of the PPA, as well as the future electricity generation. The resulting costs per unit of energy at each delivery time are then discounted using an interest rate that reflects both the general market conditions and the specific risk of the project. Given the relevance of LCOE calculations in the assessment of energy projects, a significant number of contributions are focused on proposing methods to assess the impact of relevant variables and risks.

In the case of energy projects based on RE technologies, the LCOE is affected by the uncertainty of the amount and time of production caused by the availability of resources, such as wind or solar radiation (Bruck et al., 2018). At portfolio level, such risks can be diversified-out by optimizing the technology and location mix, given that the electricity generation among different locations is uncorrelated (Gabrielli et al., 2022). Another relevant source of uncertainty regarding the appraisal of RE's LCOE is the OPEX that will be required to deliver the electricity (Mendicino et al., 2019; Bruck et al., 2018) and the availability of complementary revenues, such as subsidies or green certificates (Bruck and Sandborn, 2021). The impact of these uncertainties on LCOE and, hence, on the value of RE PPA, is often assessed using sensitivity analysis tools such as NREL's SAM (Freeman et al., 2018) and results in an increasing cost of electricity for the offtaker. Alongside the expected costs and revenues, the value of LCOE is also highly sensitive to the interest rate used to discount the cash and energy flows. In this regard, the proposed methods include the assumption of a specific market benchmark based on closed deals or on the basis of Capital Asset Pricing Models (CAPM) with betas borrowed from proxys, such as publicly traded RE companies. The resulting discount rates are often inconsistent (Steffen, 2020), an issue that can negatively affect the soundness of LCOE valuations.

Real options have been used as an alternative, or complementary, to LCOE valuation methods for RE PPAs. Thus, by analysing the set of choices for the producer throughout the investment process, it is possible to assess the impact of different sources of uncertainty on the value of the PPA. For this purpose, relevant insights have been suggested, including the potential impact of CAPEX volatility in creating incentives to defer PPA investments (Cuervo et al., 2021) and the effects of regulatory uncertainty and project execution time on the value of RE projects (Kim et al., 2017).

Literature focused on the valuation of PPAs from the perspective of the offtaker is scarce. Often valuations are based on the assumption that an RE PPA is equivalent to a swap between two parties (Edge, 2015; Peña et al., 2022), where the offtaker pays a fixed amount for the electricity and the producer a variable amount so as to purchase it from the electricity market. This approach implies that PPA offtakers obtain value in reducing the volatility of their energy costs, as they enter into the deal in order to fix the price of their future energy needs. Then, as in any swap, the fair price of the PPA is the one that makes the value of the swap at the initial time equal to zero. After that, the value of the PPA for the offtaker will vary, depending on the evolution of P_t. The swap approach implies that the value of the PPA will be always negative for one of the parties, as the net value has to be zero. This can be a valid assumption for virtual or off-site PPAs not backed by production where the producer must buy the electricity in the electricity market at any time. Nevertheless, it becomes inadequate for the appraisal of RE PPAs since, in this case, the cost of the energy for the producer is given by the LCOE and not by the electricity market price (P_t). In this regard, the relationship between the value of RE PPA for the offtaker and for the producer is determined by the credit risk, so its assessment represents a relevant issue that has not yet been sufficiently addressed. According to this last point, reduced form and structural models are the mainstream approaches to credit risk modelling. Thus, while reduced form models assume that defaults are driven by exogenous events of a purely stochastic nature, structural models provide an explicit relationship between the default risk and the value of the asset from the debtor perspective (the offtaker in the PPA case). The structural approach is considered adequate for estimating the probability of default of an RE PPA because the main driver of value for the offtaker, i.e., the difference between the cost of energy in the market and in the PPA, can be modelled with a reasonable degree of confidence as relevant and sound methodologies and data are available.

All in all, the main contributions of the present manuscript are:

- A new methodology to assess RE PPAs which takes into consideration the implicit value of reducing electricity volatility for the offtaker.
- The modelling approach also provides the default probabilities at any given time and the expected loss for the producer.
- Also collateral requirements for the offtaker can be estimated. In this respect, we have observed that the amount of guarantees demanded from the offtaker can be reduced.
- As a by-product, a well-known electricity price model is presented and its calibration according to the Iberian electricity market data is conducted.

The rest of the paper is organized as follows. In Section 2, a contingent-claim valuation model for on-site RE PPAs is proposed as the basis of a structural credit risk model of the default probability of the offtaker. In Section 3 we describe the stochastic model for the evolution of electricity prices and the estimation of the involved parameters for a given set of real data. Note that alternative models could be used. In Section 4 we apply the proposed methodology to the assessment of an RE PPA in Spain as an example, and the results are presented and discussed. Finally, a conclusion section (Section 5) is included in order to highlight the contributions of this paper and to identify possible further work that can be undertaken on the basis of the presented results.

2. Value and risk of an RE PPA from the perspective of the offtaker

As it has been outlined in the previous section, an RE PPA involves two parties: the one who purchases power (the offtaker) and the one who sells it (the producer). In this section we propose a model to assess the value of the RE PPA for the former as a result of reductions in the electricity price and its volatility. This is facilitated by analysing the optional component of an RE PPA in relation to the alternative sources of energy for the offtaker which determines to what extent the offtaker is better off in the RE PPA or in the electricity market. On this basis, it is possible to produce a complete assessment of the RE PPA value and risk from both the offtaker's and the producer's perspectives. The required inputs for such assessment must contain the specific terms of the PPA including the amount, delivery schedule and electricity price as well as a model of the alternative electricity market suited to producing realistic price samples according to the historical time series. Once the value of the RE PPA for the offtaker has been estimated, the default probabilities can be determined at any time considering the probability that the value of the PPA becomes negative. At this point, it is possible to assess the remaining risk measurements including the expected loss and the risk premium of the cost of capital.

2.1. Value of the RE PPA

Let us assume that an RE PPA contract is signed at time t_0 and expires at time t_M. In general, we assume that there are $M+1$ times to be taken into account, namely t_k, for $k = 0, \dots, M$. By entering into the RE PPA, the offtaker will receive an amount $U(t_0)$, measured in [MWh], of green power at each time at the settled price P_{PPA}. If the offtaker remains as a party in the PPA at each time t_k, then the amount $U(t_k)$ is received.

We start by considering the case $M = 1$, so that there are only two delivery times: the present time t_0 and the future time t_1. The alternative for the offtaker is to obtain that same amount of electricity at t_0 and t_1 in the electricity market at prices P_{t_0} and P_{t_1}, respectively. The value of such a PPA for the offtaker is then the present value of the expected payoffs corresponding to each of the delivery times. Thus, the payoff for the offtaker at t_0, and hence the value of the PPA at t_0, has two components. The first component, corresponding to the first electricity delivery, is the difference between the present price of the electricity in the market P_{t_0} and the price of the electricity agreed in the PPA, P_{PPA}, which we might assume that is deterministic. The second component, corresponding to the second delivery, is the present value of the difference between the electricity price in the market P_{t_1} and the electricity unit price agreed in the PPA (P_{PPA}), which has uncertainty as P_t is a stochastic variable. Since the PPA is uncollaterized, the payoff of the second period for the offtaker will never be negative, because if at t_1 P_{PPA} is greater than P_{t_1}, the offtaker would simply default from the PPA and obtain instead the required power in the electricity market. In this regard, the payoff of the PPA for the offtaker corresponding to the second period t_1 is equivalent to a European call option that matures one period later where P_t is the underlying asset and P_{PPA} is the strike price. Such payoff is given by the expression

$$H^1\left(P_{t_1}\right) = U(t_1) \cdot \max\left(P_{t_1} - P_{\text{PPA}}, 0\right).$$

Note, that in the general case, the payoff function of the European call is

$$H^k\left(P_{t_k}\right) = U(t_k) \cdot \max\left(P_{t_k} - P_{\text{PPA}}, 0\right).$$

Hence, the total value of the PPA at t_0 is given by the following formula:

$$X_0^0 = U(t_0) \cdot \left(P_{t_0} - P_{\text{PPA}} \right) + e^{-r(t_1-t_0)} H^1 \left(P_{t_1} \right). \tag{2.1}$$

Notice that the payoff of a European call option for the first period is $H^1\left(P_{t_1}\right)$ which has units of €, while the first difference has units of $\frac{€}{\text{MWh}}$, so it must be multiplied by the electricity consumption, $U(t_0)$.

For ease of simplicity, throughout this section we will consider that the offtaker receives the same amount $U\left(t_k\right) = 1\,\text{MWh}$ at each delivery date t_k, for $k = 0, \dots, M$, hence we drop the consumption variable U.

Let us now assume a PPA where $M = 2$, that is, the offtaker is offered a PPA with 3 periods where s/he can buy 1 MWh of electricity at the agreed fixed price P_{PPA}. In this case, the payoff will include the value of the difference corresponding to the second period t_1 and the last period t_2 will be the one valued as a European call option on P_{t_2} with strike P_{PPA}, starting at t_1 and maturing at t_2. Thus, in the case that the payment at t_1 has been fulfilled, the value of the PPA at t_0 is

$$X_1^0 = \left(P_{t_0} - P_{\text{PPA}} \right) + e^{-r(t_1-t_0)} \left(\left(P_{t_1} - P_{\text{PPA}} \right) + e^{-r(t_2-t_1)} H^2 \left(P_{t_2} \right) \right). \tag{2.2}$$

As presented, the PPA value for the offtaker has two components, one is given by the differences in P_{PPA} and P_{t_k} for each $k = 0, 1, \dots, M-1$ and the other is a European call option purchased at t_{M-1} and maturing at t_M. Thus, in the case that the offtaker stays in the RE PPA until the end, the value of the PPA, for a generic $M > 3$, takes the form of the following expression:

$$\begin{aligned} X_{M-1}^0 = &\left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(P_{t_1} - P_{\text{PPA}}\right) + e^{-r(t_2-t_0)} \left(P_{t_2} - P_{\text{PPA}}\right) + \cdots \\ &+ e^{-r(t_{M-1}-t_0)} \left(\left(P_{t_{M-1}} - P_{\text{PPA}}\right) + e^{-r(t_M-t_{M-1})} H^M \left(P_{t_M}\right) \right). \end{aligned} \tag{2.3}$$

Nevertheless, before the contract expiration date, t_M, there could be $M-1$ possible early terminations as the offtaker can default at any time by simply not buying the electricity from the PPA as agreed with the producer. In such a case, the offtaker will lose the right to buy any more electricity in the future from the producer at P_{PPA}. Thus, for the offtaker the value of the PPA depends on whether or not s/he will default, as any early termination is possible and each of the possible $M-1$ defaults has a different payoff. Following the same methodology as before, if $M = 2$, the possible values that the PPA at t_0 can take, depending on the possible times of early termination, are given by:

$$\begin{cases} X_0^0 = & \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} H^1 \left(P_{t_1}\right) \\ X_1^0 = & \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(\left(P_{t_1} - P_{\text{PPA}}\right) + e^{-r(t_2-t_1)} H^2 \left(P_{t_2}\right) \right), \end{cases} \tag{2.4}$$

where the former value corresponds to the scenario in which the offtaker defaults at t_1 and the latter corresponds to the scenario where the offtaker complies with the PPA terms at time t_1, hence buying the call option with maturity time t_2. As defaulting in the last period is costless for the offtaker in terms of losing the remaining options to buy electricity at P_{PPA}, the payoff of that period is embedded in the payoff of the previous period and is equivalent to the described European call option.

For $M = 3$, the PPA value has to take into account the 2 possible moments of early termination before t_3, so the possible values of the PPA are

$$\begin{cases} X_0^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} H^1 \left(P_{t_1}\right) \\ X_1^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(\left(P_{t_1} - P_{\text{PPA}}\right) + e^{-r(t_2-t_1)} H^2 \left(P_{t_2}\right) \right) \\ X_2^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(P_{t_1} - P_{\text{PPA}}\right) \\ \qquad + e^{-r(t_2-t_0)} \left(\left(P_{t_2} - P_{\text{PPA}}\right) + e^{-r(t_3-t_2)} H^3 \left(P_{t_3}\right) \right), \end{cases} \tag{2.5}$$

where the first two expressions gather the default option prior to time t_3 and the latter considers the call option maturing at t_3 obtained by not having defaulted at t_2.

Therefore, for a generic case with $M > 3$, we have to consider the $M-1$ scenarios corresponding to potential early terminations of the offtaker, which have the following different payoffs for the offtaker:

$$\begin{cases} X_0^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} H^1 \left(P_{t_1}\right) \\ X_1^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(\left(P_{t_1} - P_{\text{PPA}}\right) + e^{-r(t_2-t_1)} H^2 \left(P_{t_2}\right) \right) \\ X_2^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(P_{t_1} - P_{\text{PPA}}\right) \\ \qquad + e^{-r(t_2-t_0)} \left(\left(P_{t_2} - P_{\text{PPA}}\right) + e^{-r(t_3-t_2)} H^3 \left(P_{t_3}\right) \right) \\ \vdots \\ X_{M-2}^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + \cdots + e^{-r(t_{M-2}-t_0)} \left(\left(P_{t_{M-2}} - P_{\text{PPA}}\right) \right. \\ \qquad \left. + e^{-r(t_{M-1}-t_{M-2})} H^{M-1} \left(P_{t_{M-1}}\right) \right) \\ X_{M-1}^0 = \left(P_{t_0} - P_{\text{PPA}}\right) + \cdots + e^{-r(t_{M-2}-t_0)} \left(P_{t_{M-2}} - P_{\text{PPA}}\right) \\ \qquad + e^{-r(t_{M-1}-t_0)} \left(\left(P_{t_{M-1}} - P_{\text{PPA}}\right) \right. \\ \qquad \left. + e^{-r(t_M-t_{M-1})} H^M \left(P_{t_M}\right) \right). \end{cases} \tag{2.6}$$

Any of the early termination scenarios are available for the offtaker so, as a rational agent, the one with maximum payoff will be chosen. For this reason, the PPA value for the offtaker, which is denoted by V_{PPA}, will be given by the maximum of the possible values of the PPA, that is:

$$\begin{aligned} V_{\text{PPA}}(t_0) = \max\big(&\left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} H^1 \left(P_{t_1}\right), \\ &\left(P_{t_0} - P_{\text{PPA}}\right) + e^{-r(t_1-t_0)} \left(\left(P_{t_1} - P_{\text{PPA}}\right) \right. \\ &\quad \left. + e^{-r(t_2-t_1)} H^2 \left(P_{t_2}\right) \right), \\ &\quad \dots, \\ &\left(P_{t_0} - P_{\text{PPA}}\right) + \cdots + e^{-r(t_{M-2}-t_0)} \left(\left(P_{t_{M-2}} - P_{\text{PPA}}\right) \right. \\ &\quad \left. + e^{-r(t_{M-1}-t_{M-2})} H^{M-1} \left(P_{t_{M-1}}\right) \right), \\ &\left(P_{t_0} - P_{\text{PPA}}\right) + \cdots + e^{-r(t_{M-1}-t_0)} \left(\left(P_{t_{M-1}} - P_{\text{PPA}}\right) \right. \\ &\quad \left. + e^{-r(t_M-t_{M-1})} H^M \left(P_{t_M}\right) \right) \big), \end{aligned} \tag{2.7}$$

which can be written in a more manageable notation as follows:

$$V_{\text{PPA}}(t_0) = \max_{1 \le m \le M} \left(\sum_{j=0}^{m-1} e^{-r(t_j-t_0)} \left[P_{t_j} - P_{\text{PPA}} \right] + e^{-r(t_{m-1}-t_0)} e^{-r(t_m-t_{m-1})} H^m \left(P_{t_m}\right) \right). \tag{2.8}$$

In order to assess the value of the PPA for the offtaker at any arbitrary time t_k, with $k = 0, \dots, M-1$, the following expression can be used:

$$V_{\text{PPA}}(t_k) = \max_{k+1 \le m \le M} \left(\sum_{j=k}^{m-1} e^{-r(t_j-t_k)} \left[P_{t_j} - P_{\text{PPA}} \right] + e^{-r(t_{m-1}-t_k)} e^{-r(t_m-t_{m-1})} H^m \left(P_{t_m}\right) \right), \tag{2.9}$$

where P_{t_k} is the electricity market price at time t_k. Therefore, the expected value of the PPA is given by Glasserman (2003)

$$\mathbb{E}\left[V_{\text{PPA}}(t_k) \mid V_{\text{PPA}}(t_{k-1}) > 0 \right], \quad k \ge 1. \tag{2.10}$$

In this sense, the PPA value is a path-dependent derivative.

2.2. Credit risk of an RE PPA

The importance of the default probability has been extensively studied in the literature. Furthermore, a variety of models exist which are included in commercial software toolboxes (Crosbie and Bohn, 2019; Nazeran and Dwyer, 2015). Such models share a starting point: Merton's paper on liabilities (Merton, 1974), which provides an analytical solution. Nevertheless, more complex underlying asset models make an analytical solution for the default probability impractical. In the following lines we define the default probability for the offtaker on the basis of the main source of risk for him/her: the evolution of the market price of the electricity. In order to assess the adequate level of guarantees that the producer needs to hedge the asset, it must be assumed that the risk price drives the default probability of the offtaker. Then, the risk assessment of the guarantees themselves must be carried out independently.

Thus, at any given time t_k ($k = 0, \dots, M-1$), the probability of default of the PPA, denoted as $PD(t_k)$, is the probability that the value for the offtaker $V_{\mathrm{PPA}}(t_k)$ is less than or equal to 0. As the PPA can only default one time, $PD(t_k)$ is conditional on the PPA not having defaulted at any prior time. This means that if at time t_k none of the alternative payoff scenarios that are available for the offtaker have a positive value, the rational decision for him/her is to quit the PPA and, from that time on, obtain instead the electricity from the market at P_t. Thus, $PD(t_k)$ of the PPA at any time t_k is given by:

$$PD(t_0) = \mathbb{P}\left[V_{\mathrm{PPA}}(t_0) \le 0\right] \tag{2.11}$$

$$PD(t_k) = \mathbb{P}\left[V_{\mathrm{PPA}}(t_k) \le 0 \mid V_{\mathrm{PPA}}(t_{k-1}) > 0\right] \quad \text{for } k = 1, \dots, M-1, \tag{2.12}$$

In order to estimate such probability, let us introduce some notation. Let the possible alternative scenarios for the offtaker evaluated at t_0 be given by the set $\{X_0^0, \dots, X_{M-1}^0\}$. Then, for $0 \le k \le M-1$ we have:

$$\begin{aligned}
X_k^k &= \sum_{j=k}^{k} \left(P_{t_j} - P_{\mathrm{PPA}}\right) e^{-r(t_j - t_k)} + e^{-r(t_{k+1}-t_k)} H^{k+1}\left(P_{t_{k+1}}\right) \\
X_{k+1}^k &= \sum_{j=k}^{k+1} \left(P_{t_j} - P_{\mathrm{PPA}}\right) e^{-r(t_j - t_k)} + e^{-r(t_{k+2}-t_k)} e^{-r(t_{k+2}-t_{k+1})} H^{k+2}\left(P_{t_{k+2}}\right) \\
&\vdots \\
X_{M-1}^k &= \sum_{j=k}^{M-1} \left(P_{t_j} - P_{\mathrm{PPA}}\right) e^{-r(t_j - t_k)} + e^{-r(t_{M-1}-t_k)} e^{-r(t_M-t_{M-1})} H^{M}\left(P_{t_M}\right).
\end{aligned} \tag{2.13}$$

Therefore, the probability of default for the offtaker at time t_k is given by the probability that none of the X_j^k payoffs, for $j = k, \dots, M-1$, has a value greater than or equal to 0.

2.3. Expected loss, collateral requirements and risk premium

The estimation of the default probabilities corresponding to each period of the PPA allows for the calculation of the expected loss for the producer in case of default. Thus, at any given time t_k, one can assume that such loss is equivalent to the investment that has not yet been recovered, which is the CAPEX that has not been amortized. In real conditions, the estimation of the loss for the producer in case of default includes an exhaustive assessment, which can be included in the model. Therefore, for $k = 0, \dots, M-1$, the expected loss for the producer at time t_k is given by:

$$\begin{aligned}
EL\left(t_k\right) &= PD\left(t_k\right) \cdot CAPEX^{\text{not}}_{\text{amortized}}\left(t_k\right) \\
&= PD\left(t_k\right) \cdot \left(CAPEX\left(t_k\right) - AMORTIZATION\left(t_k\right)\right),
\end{aligned} \tag{2.14}$$

which, in the case of a linear amortization, takes the following form:

$$EL\left(t_k\right) = PD\left(t_k\right) \cdot CAPEX\left(t_0\right)\left(1 - \frac{t_k - t_0}{t_{M-1} - t_0}\right) \tag{2.15}$$

Thus, the total expected loss at t_0 is the sum of the present value of the expected loss at each time and is given by

$$TEL\left(t_0\right) = \sum_{k=0}^{M-1} e^{-r(t_k - t_0)} EL\left(t_k\right) \tag{2.16}$$

In order to hedge the credit risk of the RE PPA the producer must demand from the offtaker to provide guarantees amounting to $TEL(t_0)$ with the required level of confidence. The credit risk of $TEL(t_0)$ will depend on the credit quality of the specific guarantees provided by the offtaker.

3. Electricity price model

A variety of electricity price models are available in the related literature, see for instance (Kluge, 2006), where a brief yet complete review was conducted, and the articles cited therein. Among other options, regime-switching and jump-diffusion models are extensively used. The former usually aims to take into consideration the impact of a downturn and global events (such as a global pandemic, a war, etc.) (Goutte and Zou, 2013) while the latter takes into account features such as the non-storability of electricity (on a large scale at least) and outages or surplusses of electricity production (Cartea and Figueroa, 2005; Weron et al., 2004). In addition to this, electricity price models can include a seasonality (deterministic) function, so that the problem is usually decomposed into a pure stochastic process which might be a mean-reversion with jumps process, plus a deterministic function (Calvo-Garrido et al., 2019). In the present work, we have chosen the following decomposition of the electricity price:

$$P_t = f(t) + Y_t, \tag{3.1}$$

where $f(t)$ represents the seasonality function and Y_t is the stochastic part of the price process, in which we incorporate a Markov regime-switching model, given by:

$$Y_t = \begin{cases} Y_{t,b} & \text{if } R_t = b \\ Y_{t,s} & \text{if } R_t = s \\ Y_{t,d} & \text{if } R_t = d, \end{cases}$$

where $\{b, s, d\}$ stands for base, spike and drop regimes, respectively. The switching mechanism between the states is Markovian and is given by an unobserved latent random variable (Janczura and Weron, 2010). Therefore, the stochastic part of the electricity price switches from one regime to another according to the transition probability matrix

$$P = \begin{pmatrix} p_{bb} & p_{bs} & p_{bd} \\ p_{sb} & p_{ss} & p_{sd} \\ p_{db} & p_{ds} & p_{dd} \end{pmatrix}, \quad \text{with} \quad p_{ii} = 1 - \sum_{i \ne j} p_{ij}. \tag{3.2}$$

Concerning the stochastic part, first, since in practice the electricity price exhibits a mean reversion feature, the base regime is given by a mean-reverting process satisfying the following stochastic differential equation (see Janczura and Weron (2012) and Janczura and Weron (2014), for example):

$$dY_{t,b} = \left(\alpha - (1-\beta) Y_{t,b}\right) dt + \sigma_b \left|Y_{t,b}\right|^{\gamma} dW_t, \tag{3.3}$$

where $Y_{t,b}$ is the deseasonalized price of electricity in the base regime. The constant values $(1-\beta)$, $\alpha/(1-\beta)$ and σ_b represent the speed of mean reversion, the long term value and the volatility of the deseasonalized price of electricity in the base regime, respectively. Moreover, as indicated in Janczura and Weron (2010), the parameter γ represents the degree of inverse leverage observed in electricity prices. Furthermore, W_t represents the Brownian motion process at time t. After discretization in time with Euler–Maruyama method with time step $\Delta t = 1$, we get

$$Y_{t,b} = \alpha + \beta Y_{t-1,b} + \sigma_b \left|Y_{t-1,b}\right|^{\gamma} \varepsilon_t, \tag{3.4}$$

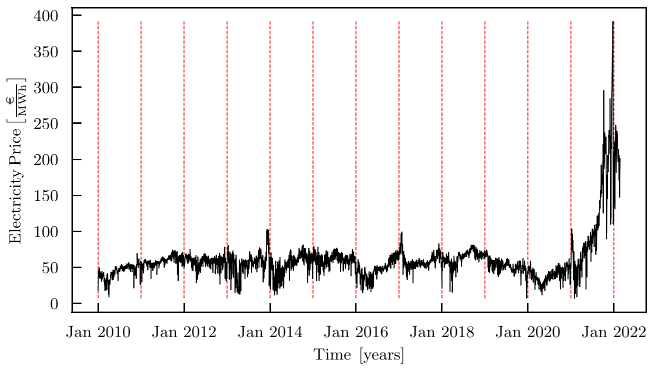

Fig. 1. Daily electricity market price for consumers in Spain from January 1, 2010, until February 24, 2022. Red-dotted lines represent a new year.

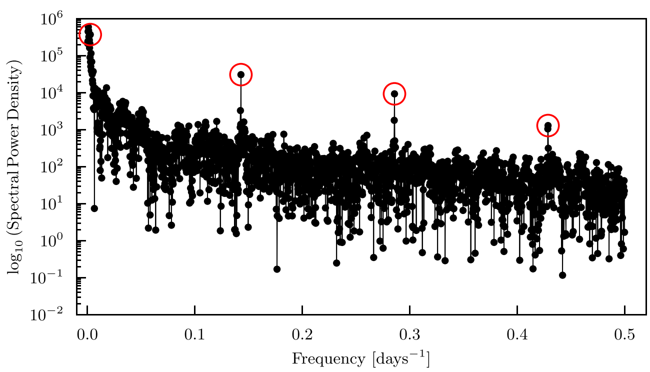

Fig. 2. Periodogram of the daily electricity prices. Y-axis is in log-scale. Red circles show the maxima of the periodogram.

where $\varepsilon_t \sim \mathcal{N}(0,1)$. The spike regime incorporates sudden price jumps and is given by the lognormal random variables

$$\log\left(Y_{t,s} - Y\left(q_s\right)\right) \overset{\text{iid}}{\sim} \mathcal{N}(0,1), \tag{3.5}$$

whereas the probability distribution of the drop regime is assumed as follows

$$\log\left(Y\left(q_d\right) - Y_{t,d}\right) \overset{\text{iid}}{\sim} \mathcal{N}(0,1). \tag{3.6}$$

In expressions (3.5) and (3.6), $Y\left(q_i\right)$ with $i = \{s,d\}$ represents the q_i-quantile of the dataset (Janczura and Weron, 2012, 2010). Note that given these quantiles, prices above $Y\left(q_d\right)$ will have zero probability of belonging to the drop regime and prices below $Y\left(q_s\right)$ will have zero probability of belonging to the spike regime (Janczura and Weron, 2010).

Upon the specification of the model, the parameter estimation based on historical daily electricity prices remains to be done. The obtained data from Red Eléctrica de España (2022) will allow us to characterize our model of electricity prices with the aforementioned features. Data selection is due to the ever-growing photovoltaic facilities in the Mediterranean region, namely in Spain, and hence, the necessity for a credit risk valuation. The selected time period ranges from 2010 to 2022, thus avoiding the extraordinary volatility of the electricity markets caused by the invasion of Ukraine in February 2022.

Note that several approaches might be applied, including: dummy variables which are able to take into consideration holidays and weekends (Lucia and Schwartz, 2002), Fourier decomposition (Cartea and Figueroa, 2005) and wavelets (Janczura and Weron, 2010), this latter one being a good approach for deseasonalizing data. However, although useful for fit-in purposes, outlier replacement and short-term forecasting, wavelets do not provide good results in terms of long term forecasting (Janczura and Weron, 2010; Janczura et al., 2013). Note that in PPA pricing we require long term forecasting of electricity prices.

Table 1
Estimated parameters of the seasonality function.

	i				
	1	2	3	4	5
a_i	12.094290	−3.958406	−2.359212	39.088134	−37.975025
τ_i	−50.232955	1.635209	1.680183	−6.146994	4.606856

At first glance, our raw data (see Fig. 1) do not seem to follow a pattern beyond weekly peaks, so we will follow the methodology proposed in Weron et al. (2001) in order to discover any other type of seasonality. A discrete Fourier transformation allows us to change from the time domain to the frequency domain, thus we can observe a pattern wherever it exists. Instead of dealing with the outcomes of the Fourier transformation, we will use the periodogram graph as suggested in Weron et al. (2001), which describes how the power is distributed among frequencies and it is implemented in Virtanen et al. (2020). If we plot this kind of spectral density we obtain Fig. 2, where several maxima are observed. We will focus especially on those which are separate from each other at a certain frequency. For this reason, we see 3 peaks at frequencies $0.142889\,\text{days}^{-1}$, $0.285779\,\text{days}^{-1}$ and $0.428668\,\text{days}^{-1}$. Moreover, taking into account the frequency value $\nu = \frac{1}{T}$, the periodicities of these peaks are, respectively, 6.998439, 3.499207 and 2.332808 days, so that we conclude that both a weekly and intra-weekly pattern exist. Concerning the other peaks, we see that there are 2 dominant peaks at frequencies $0.000902\,\text{days}^{-1}$ and $0.002705\,\text{days}^{-1}$, the latter corresponding to 369.750012 time periods (days), that is, a yearly pattern exists.

In order to remove this seasonal pattern, we will consider cosine functions for both weekly and yearly patterns (see Kluge (2006)) instead of a moving average for the intra-weekly pattern (Weron et al., 2001). Therefore, initially we consider the following seasonality function:

$$f(t) = \sum_{i=1}^{4} a_i \cos\left(2\pi\gamma_i\left(t-\tau_i\right)\right), \tag{3.7}$$

where $\gamma_1 = \frac{1}{365}$ and $\gamma_2 = \frac{1}{7}$ are used for the yearly and weekly seasonality patterns, respectively, while $\gamma_3 = \frac{1}{7/2}$ and $\gamma_4 = \frac{1}{7/3}$ are considered for the intra-weekly seasonalities. Nevertheless, an additional term was added to Eq. (3.7) due to the fact that the periodogram of the deseasonalized electricity market prices associated to the previous choice exhibited a peak, that is, a periodicity still remained. This additional term modifies Expression (3.7) as follows

$$f(t) = \sum_{i=1}^{5} a_i \cos\left(2\pi\gamma_i\left(t-\tau_i\right)\right), \tag{3.8}$$

where $\gamma_5 = \frac{1}{7/4}$.

Note that expression (3.8) can be represented as a linear combination of sines and cosines by means of appropriate trigonometric identities (Kluge, 2006). The parameters a_i and τ_i for $i = 1,\dots,5$ are chosen so that the squared error $\sum_i \left(P_i - f(t_i)\right)^2$ is minimized. This minimization problem has been solved by means of the Nelder–Mead method implemented in Virtanen et al. (2020) and the obtained results are shown in Table 1.

As soon as the deseasonalized data have been recovered ($Y_t = P_t - f(t)$), the periodogram can once again be plotted and checked that no periodicities remain. The electricity price and the seasonality function are presented in Fig. 3. Eventually, we obtain the parameters of the stochastic part of the model, which were estimated by means of the Expectation-Maximization algorithm. This algorithm takes into account the latent nature of the regimes given the observations and it is comprised of 2 steps: the Expectation step and the Maximization step. The former one, likewise, is composed of 2 steps: firstly, by the

Table 2
Parameter estimation (first column) of the sample data considered (from January 1, 2010, until February 24, 2022) and re-estimation of parameters given the number of observations $N_{obs} = 100, 200, 500, 1000, 2000, 4437$, being this latter value the number of electricity market price observations. Values are averaged over 1000 trajectories. $\mathbb{P}[i]$ for $i = \{b, s, d\}$ represents the constant unconditional probability of belonging to regime i.

	Empirical	Simulated					
	$N_{obs} = 4437$	$N_{obs} = 100$	$N_{obs} = 200$	$N_{obs} = 500$	$N_{obs} = 1000$	$N_{obs} = 2000$	$N_{obs} = 4437$
α	0.911431	0.819226	0.871061	0.899664	0.908388	0.912800	0.914409
β	5.023233	9.867072	7.622353	6.094488	5.239531	4.945982	4.854042
σ_b^2	0.396413	0.544214	0.578973	0.464651	0.410823	0.408744	0.409020
γ	0.500000	0.500000	0.500000	0.500000	0.500000	0.500000	0.500000
μ_s	4.418186	2.811052	2.935040	3.297634	3.682807	3.949635	4.215023
σ_s^2	0.420497	0.056691	0.105374	0.222811	0.318585	0.414000	0.499420
μ_d	3.045841	2.649513	2.779976	2.898777	2.931749	2.954147	2.953547
σ_d^2	0.135686	0.325043	0.271225	0.199297	0.176242	0.161191	0.158605
p_{bb}	0.982957	0.929006	0.953190	0.970244	0.979065	0.981640	0.982035
p_{ss}	0.993208	0.624573	0.628684	0.753925	0.831365	0.912026	0.970128
p_{dd}	0.904341	0.784244	0.851124	0.897793	0.907296	0.911295	0.912122
$\mathbb{P}[b]$	0.772927	0.786743	0.813792	0.810803	0.822347	0.820641	0.795276
$\mathbb{P}[s]$	0.096192	0.064009	0.050911	0.039658	0.020585	0.020382	0.049060
$\mathbb{P}[d]$	0.130881	0.149248	0.135297	0.149539	0.157068	0.158977	0.155664

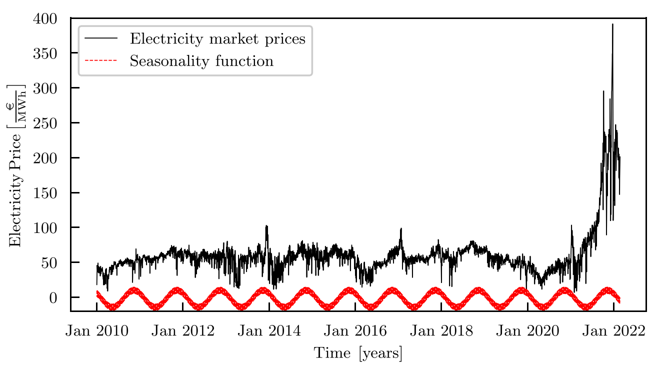

Fig. 3. Electricity market price data (black) and seasonality function (red). Seasonality function is given by Eq. (3.8) and estimated parameters are those of Table 1.

Bayes rule, the probability of being in a given state at time t conditioned on the observations up to time t and the estimated parameters is computed (forward in time) and secondly the probability of belonging to a given state at time t conditioned on the whole set of observations is computed (backward in time), also known as smoothed probabilities. Eventually, the Maximization step takes place and the (log)likelihood of the model is computed and the parameters which maximize the (log)likelihood are obtained. These consecutive steps are repeated until a (local) maximum is achieved (Janczura and Weron, 2012). Here we have followed the methodology applied in Janczura and Weron (2012) and we seize the publicly available scripts of the authors (Janczura and Weron, 2011a,b). According to that estimation, Fig. 4 was obtained, where if the probability of being in a given regime at time t given the observations up to time T (the so-called smoothed probabilities) is greater than 0.5 then the observation is coloured according to that regime.

After the values of the parameters have been estimated, in order to check the adequacy of the proposed model and its calibrated parameters, we perform a re-estimation of the parameters (see Table 2) with the proper discretization and average over 1000 sample paths of the process. Also this allows for the comparison between the moments of the deseasonalized electricity market price data and the moments of the sample paths (see Table 3) and to visually check the trajectories (see Fig. 5) (Janczura and Weron, 2012; Geman and Roncoroni, 2006).

Furthermore, in Appendix B we have summarized additional metrics between the dataset and the simulated trajectories.

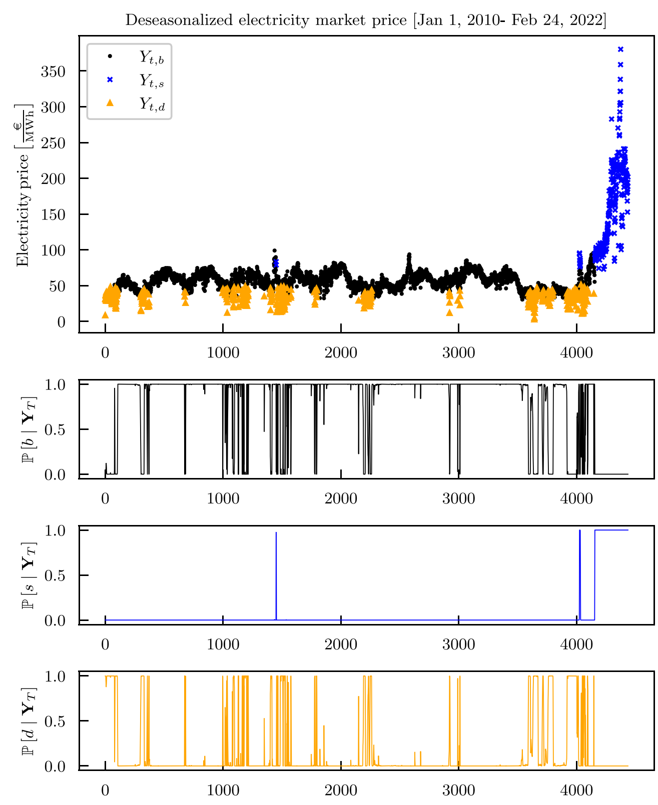

Fig. 4. Parameters estimation of a Markov regime switching model with three independent regimes given by Eqs. (3.4), (3.5) and (3.6), where both spike and drop regimes are shifted lognormals and the cutoff is considered $q_s = q_d = 0.5$, that is, the median. Top: represents the state each observation belongs to, where an observation is considered as belonging to a given state if $\mathbb{P}\left[R_t = i \mid Y_1, \dots, Y_T\right] > 0.5$ for $i = \{b, s, d\}$. These probabilities (also known as smoothed probabilities within the framework of the Expectation-Maximization algorithm) are represented in the 3 lower panels. For the sake of brevity, smoothed probabilities are denoted as $\mathbb{P}\left[R_t = i \mid Y_1, \dots, Y_T\right] = \mathbb{P}\left[i \mid \mathbf{Y}_T\right]$ for $i = \{b, s, d\}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Results and discussion

Once the electricity price model has been fully specified, we are able to generate paths of the underlying asset of the RE PPA, that is, the electricity market price, and apply the aforementioned valuation framework in Section 2 and the numerical methods described in Appendix A.

Table 3
Moments of the sample data (first column) considered (from January 1, 2010, until February 24, 2022) and computed moments given the number of observations N_{obs} = 100, 200, 500, 1000, 2000, 4437, being this latter value the number of electricity market price observations. Moments are averaged over 1000 trajectories for the given range of simulated observations.

	Empirical	Simulated					
	$N_{obs} = 4437$	$N_{obs} = 100$	$N_{obs} = 200$	$N_{obs} = 500$	$N_{obs} = 1000$	$N_{obs} = 2000$	$N_{obs} = 4437$
Mean	60.848246	51.220234	55.816331	59.856471	61.813034	62.435138	62.972081
Std	32.584061	16.494049	19.524730	25.360192	30.575096	33.747465	37.176545
Skewness	3.884989	−0.276703	0.057311	1.020683	2.124778	3.235716	4.503992
Kurtosis	20.018736	0.895167	1.684636	7.934908	17.088082	28.723874	41.995153

Table 4
Parameter specification for a photovoltaic irrigation facility in Spain and the corresponding notation according to the valuation Section 2 is given in parentheses.

Lifespan (t_M)	Payments	LCOE (P_{PPA})
20 years	One per year	76.69 $\frac{€}{\text{MWh}}$
Amortizations $(AMORTIZATION\,(t_k))$	CAPEX $(CAPEX^{\text{not}}_{\text{amortized}}(t_k))$	Interest rate (r)
0 € for year 0, 11 484 € for years 1–10 and 13 012 € for years 11–19	244 960 € for year 0 $CAPEX(t_{k-1}) - AMORTIZATION(t_k)$ for years 1–19	2%

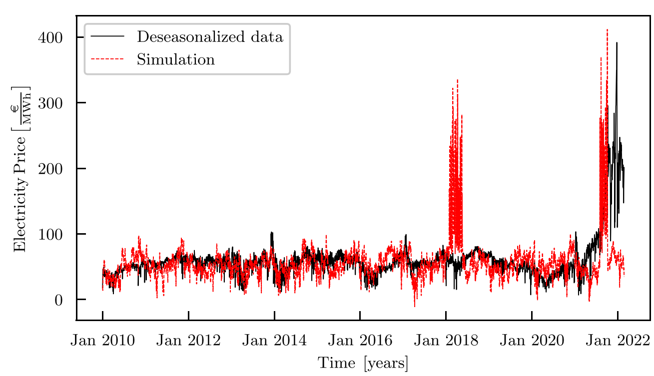

Fig. 5. Comparison of real and simulated paths of deseasonalized electricity market prices P_t.

In order to present a practical implementation of the proposed methodology, based on an RE PPA designed for a photovoltaic irrigation project in Spain (Carrêlo et al., 2020), a case study has been analysed. The results obtained for the value of the PPA for the offtaker and the credit risk assumed by the producer are discussed in comparison with two alternative valuations of the same system that do not take the optional value for the offtaker into account.

Aiming to address the annual energy needs for the offtaker totalling 300 MWh (i.e., $U(t_i) = 300\,\text{MWh}$, $i = 0, \ldots, M$), the producer estimates that a 200 kWp RE system will be required, at a cost (CAPEX) of 244 960 €. The PPA will last 20 years and the billing of the electricity will take place in advance on an annual basis. The amortization of the investment will be carried out linearly during the 20 years of the contract lifespan. For the purpose of establishing a price for the PPA, the producer has calculated that the LCOE of the system is 76.69 $\frac{€}{\text{MWh}}$ (see Pombo Romero and Paniego Moya (2021) for further details). The current electricity market price from the grid has been calculated as the average price in the fourth quarter of 2022, which is $P_{t_0} = 143.17\,\frac{€}{\text{MWh}}$ and we have assumed that the initial value belongs to the base regime. The input variables at a system level are presented in Table 4.

The alternative source of energy for the offtaker can be obtained by purchasing electricity from the public grid at market price, so the value of the PPA for the offtaker depends on its capability to generate savings in cost and to reduce volatility in relation to the market prices. In order to simplify the model, all prices and discount rates are presented in real terms (no inflation is assumed).

4.1. PPA value

According to the proposed methodology, the expected value of the described RE PPA for the offtaker is $\mathbb{E}_{t_0}\left[V_{\text{PPA}}(t_0)\right] = 38\,111.64$ € for a $P_{\text{PPA}} = \text{LCOE} = 76.69\,\frac{€}{\text{MWh}}$, with 95% CI equal to (36 113.37, 40 109.91). In this case, P_{PPA} is lower than the current electricity price, P_{t_0}. As a result, the PPA delivers value for the offtaker, both from reductions in the cost of electricity and in its volatility. Resulting valuations differ from those obtained using a conventional, swap-based approach (Edge, 2015), where the value is given by the following expression:

$$V_{\text{PPA}}\left(t_k\right) = \sum_{i=k}^{M} U(t_i)\left(P_{t_i} - P_{\text{PPA}}\right) e^{-r\left(t_i - t_k\right)}, \quad \text{for } k = 0, \ldots, M. \tag{4.1}$$

Furthermore, we also have considered a modified version of the above expression which takes negative prices into account, since negative electricity prices must be considered and, as a matter of fact, such values have been observed in the German electricity market due to the mix of an increasing renewable generation and a low demand (Genoese et al., 2010).

$$V_{\text{PPA}}\left(t_k\right) = \sum_{i=k}^{M} U(t_i)\left(P_{t_i} - P_{\text{PPA}}\right) e^{-r\left(t_i - t_k\right)} \mathbb{1}_{\{P_{t_i} > 0\}}, \quad \text{for } k = 0, \ldots, M, \tag{4.2}$$

where, $\mathbb{1}_{\{P_{t_i} > 0\}}$ takes the value 1 if $P_{t_i} > 0$ and 0 otherwise.

Such differences are shown in Fig. 6, which presents the expected value of the PPA for the offtaker for a range of possible P_{PPA} prices resulting from Eqs. (2.8), (4.1) and (4.2). Nevertheless, such plot does not show any significantly difference between the expression with indicator function (Eq. (4.2)) and the one without indicator function (Eq. (4.1)), although in Table 5 numerical values are shown providing different values. This is due to the fact that only a few paths are capable of yielding negative prices.

As expected, since Eqs. (4.1) and (4.2) do not reflect the value that the offtaker obtains by reducing uncertainty in the future cost of electricity, resulting PPA valuations are significantly lower than those produced by Eq. (2.8), which includes such a source of value. Indeed, both swap approaches yield a negative PPA value for a $P_{\text{PPA}} \in$

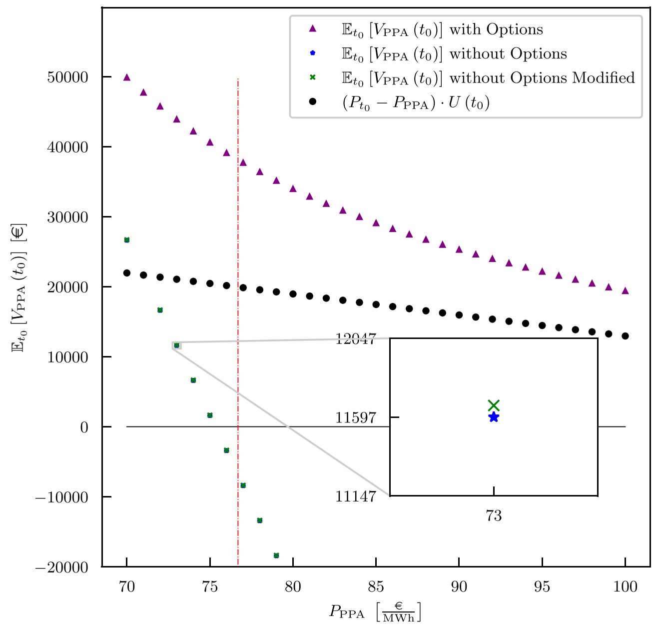

Fig. 6. Expected value of $V_{\mathrm{PPA}}(t_0)$ considering two approaches which do not offer options on the underlying asset (blue stars for the plain swap approach and green crosses for the swap approach with an indicator function, referred as Modified) and expected value of $V_{\mathrm{PPA}}(t_0)$ in our approach, which includes options (purple triangles) as functions of P_{PPA}. Black points represent the value of the first difference in prices $(P_{t_0} - P_{\mathrm{PPA}})$ multiplied by the consumption. The red-dotted line represents the LCOE value. Results were obtained for simulations starting from $P_{t_0} = 143.17 \frac{€}{\mathrm{MWh}}$, $t_M = 20$ years, $U(t_k) = 300\,\mathrm{MWh}$, $t_k = k$ for $k = 0, \dots, M$ and with $\Delta t = 1$ day, $N = 1000$ paths. For the simulation we refer to Janczura and Weron (2011b). Observe that for both swap approaches not all expected values of V_{PPA} are plotted, since for P_{PPA} values greater than 79 $\frac{€}{\mathrm{MWh}}$, the expected value remains negative.

(75, 76) and it gets even more negative as P_{PPA} increases and, hence, the PPA value for a P_{PPA} = LCOE is negative for both swap-based methodologies (Edge, 2015). In contrast, the proposed methodology in this article indicates that the PPA still has value for the offtaker at P_{PPA} levels significantly higher than the LCOE and this value is greater than the first difference of the PPA valuation, $U\left(P_{t_0} - P_{\mathrm{PPA}}\right)$, with U being the constant consumption. This feature is coherent with the general financial principle which states that a future cash flow with lower volatility is more valuable than the equivalent one with higher volatility

4.2. Credit risk

In the presented case study, P_{PPA} is significantly lower than P_{t_0}, so it is highly unlikely that the offtaker would be better off purchasing electricity from the electricity market instead, particularly during the first year. This means that the probability that the value of the PPA turning negative as a result of steep reductions in the electricity market price is relatively low in comparison with the default probability that both swap approaches yield and is shown in Table 6. The proposed model allows for the calculation of such a probability for each period, which is presented in Fig. 7.

As P_{t_0} is unusually high, the PPA starts deep in the money, so $PD(t_0) = 0$. At time t_1 the probability of default rises to a value of 0.495. This is due to the fact that at time t_1 none of the possible scenarios, that is none of X_k^1, for $k = 1, \dots, M-1$, is positive for several electricity market price trajectories. Recall the mean reversion property of the base regime and the sample data considered, where the mean value of the deseasonalized electricity market price was 60.84 $\frac{€}{\mathrm{MWh}}$. After that, the remaining electricity price trajectories which provide a positive V_{PPA} decrease slowly over time. Due to the amortization proposed in Eq. (2.14), which in our case is assumed to be a piecewise

Table 5
Expected PPA values measured in [€] for a range of P_{PPA} values measured in $\left[\frac{€}{\mathrm{MWh}}\right]$.

P_{PPA}	$\mathbb{E}_{t_0}[V_{\mathrm{PPA}}(t_0)]$ [€]		
	Our model	Swap model	Swap model modified
70	49 853.63	26 617.72	26 681.53
71	47 709.13	21 610.79	21 675.36
72	45 730.37	16 603.86	16 669.20
73	43 881.34	11 596.93	11 663.03
74	42 174.50	6590.00	6656.86
75	40 576.24	1583.07	1650.70
76	39 087.51	−3423.86	−3355.47
77	37 689.55	−8430.79	−8361.64
78	36 371.97	−13 437.71	−13 367.80
79	35 121.27	−18 444.64	−18 373.97
80	33 951.84	−23 451.57	−23 380.14
81	32 856.49	−28 458.50	−28 386.30
82	31 833.50	−33 465.43	−33 392.47
83	30 864.21	−38 472.36	−38 398.64
84	29 950.25	−43 479.29	−43 404.80
85	29 071.80	−48 486.22	−48 410.97
86	28 242.58	−53 493.15	−53 417.14
87	27 453.04	−58 500.08	−58 423.30
88	26 710.37	−63 507.01	−63 429.47
89	25 982.92	−68 513.94	−68 435.64
90	25 283.26	−73 520.87	−73 441.80
91	24 611.90	−78 527.80	−78 447.97
92	23 963.37	−83 534.73	−83 454.14
93	23 338.47	−88 541.66	−88 460.30
94	22 732.47	−93 548.59	−93 466.47
95	22 145.70	−98 555.52	−98 472.64
96	21 569.53	−103 562.45	−103 478.80
97	21 002.84	−108 569.38	−108 484.97
98	20 449.29	−113 576.31	−113 491.14
99	19 908.91	−118 583.24	−118 497.30
100	19 380.68	−123 590.17	−123 503.47

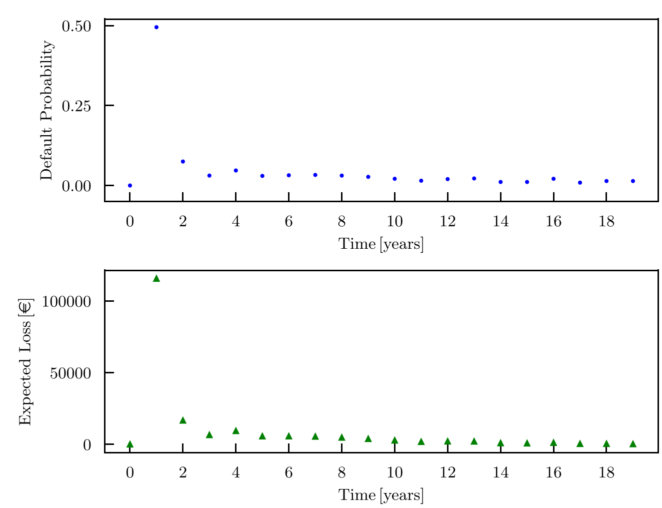

Fig. 7. Credit risk metrics for $P_{t_0} = 143.17 \frac{€}{\mathrm{MWh}}$, $P_{\mathrm{PPA}} = LCOE = 76.69 \frac{€}{\mathrm{MWh}}$ and system parameters as presented in Table 4. Default Probability (top) and Expected Loss (bottom). Numerical values for the default probability are presented in Table 6. Both plots were generated considering the model given by Eq. (2.8).

linear function (see Table 4), the expected loss behaviour will be that of the default probability.

The obtained probabilities of default provide the risk measure for the offtaker, which, in the case of an uncollateralized RE PPA, is equivalent to the credit risk. In order to assess the amount of collateral that is required to limit the credit risk at a given level, it is necessary to estimate the corresponding expected loss. As indicated, RE PPA producers are responsible for financing the project's CAPEX, which will be paid back throughout the lifespan of the project in the form of periodic amortizations. In the case of an early termination due to a default at time t_k, the expected loss for the producer depends on the

Table 6
Default probability for a P_{PPA} = LCOE = 76.69 $\frac{€}{\text{MWh}}$ for each year, computed as explained in Section 2 and Appendix A. Swap Model Modified refers to Eq. (4.2).

Time	Default probability		
	Our model	Swap model	Swap model modified
0	0.000	0.638	0.638
1	0.495	0.133	0.132
2	0.075	0.013	0.014
3	0.031	0.017	0.017
4	0.047	0.015	0.015
5	0.030	0.013	0.013
6	0.032	0.020	0.020
7	0.033	0.016	0.016
8	0.031	0.009	0.009
9	0.027	0.007	0.007
10	0.021	0.011	0.011
11	0.015	0.010	0.010
12	0.020	0.008	0.008
13	0.022	0.007	0.007
14	0.011	0.005	0.005
15	0.011	0.006	0.006
16	0.021	0.012	0.012
17	0.009	0.008	0.008
18	0.014	0.012	0.012
19	0.014	0.010	0.010

amount of CAPEX that has not been amortized at that moment. The resulting expected loss is given by Eq. (2.16) which in the presented example (P_{PPA} = LCOE) amounts to 175 537.27 €. Thus, in order to hedge the credit risk of the RE PPA, the offtaker has to provide guarantees of 175 537.27 €, which are equivalent to 71.66% of the total investment/CAPEX. In order to complete the risk assessment of the project, the producer will have to estimate the risk of the guarantees themselves or the credit rating of the offtaker, if specific guarantees are not available.

Note that the inclusion of the optional value in RE PPA valuations has a significant impact on the credit risk assessment. This is illustrated by Fig. 8, which compares the total expected loss (i.e., collateral requirements) from the here-proposed model and from the swap-based approach presented in Eqs. (4.1) and (4.2) and whose probabilities of default are computed following Eq. (2.11).

As we can see from Fig. 8, collateral requirements are significantly lower when considering the optional value of the PPA alongside its intrinsic value. The difference between both approaches tends to diminish in out-of-the-money PPAs, as the accumulated probabilities of default tend to 1, with or without considering the optional value. Although not shown here, this occurs for a $P_{\text{PPA}} > 143\,\frac{€}{\text{MWh}}$ (which is the initial electricity market price), where the $TEL\left(t_0\right)$ for the proposed model is 1% lower than that of both swap approaches and as P_{PPA} increases this difference becomes smaller. Nevertheless, for $100\,\frac{€}{\text{MWh}} \leq P_{\text{PPA}} \leq 143\,\frac{€}{\text{MWh}}$ the proposed model yields a $TEL\left(t_0\right)$ which takes values that range from 10% to 7% lower than both swap approaches. It is important to note that both swap approaches yield a $TEL\left(t_0\right)$ equal to the CAPEX for a $P_{\text{PPA}} \in (136, 137)$ and, hence, remains equal to the CAPEX for P_{PPA} values greater than that. Recall that for a $P_{\text{PPA}} = 76.69\frac{€}{\text{MWh}}$ our approach provides estimates $TEL(t_0)$ = 175 537.27 € while both swap approaches estimate $TEL(t_0)$ = 210 066.11 € and $TEL(t_0)$ = 210 050.55 €, belonging this latter result to the swap model that includes an indicator function. These results can be found in Table 7 and we can conclude that the here-proposed approach leads to collateral requirements that range from 21% to 11% lower than in a swap-approach for a $P_{\text{PPA}} \in [70, 100]$. Notice also from Table 7 that, although negligible, there exists a difference in the computed $TEL\left(t_0\right)$ for both swap approaches, since a few trajectories show negative electricity market prices.

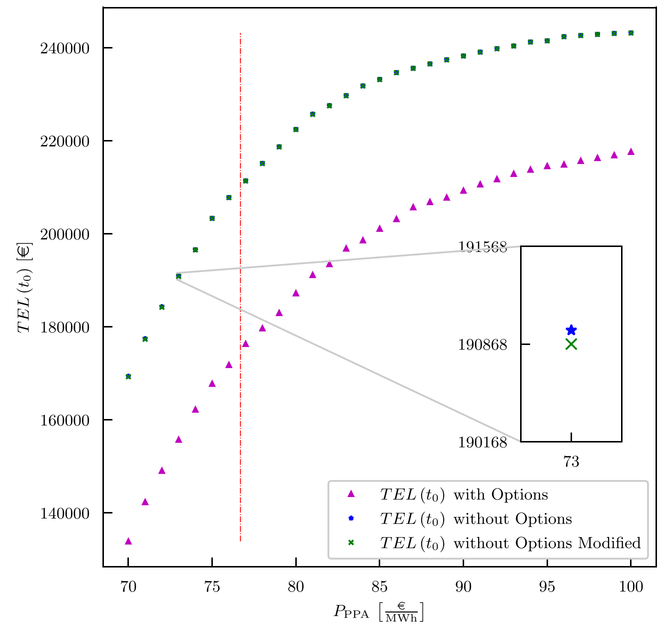

Fig. 8. $TEL\left(t_0\right)$ assuming an RE PPA without optional value (blue stars for the model without indicator and green crosses for the model which incorporates an indicator function) and $TEL\left(t_0\right)$ including the options (purple triangles) for different levels of P_{PPA}. Red-dotted line represents the LCOE value. The parameters of the electricity market price model are the same as in Fig. 6.

Table 7
$TEL\left(t_0\right)$ values in [€] for P_{PPA} values ranging from 70 $\frac{€}{\text{MWh}}$ to 100 $\frac{€}{\text{MWh}}$. Swap Model Modified refers to the swap model which incorporates an indicator function.

P_{PPA}	$TEL\left(t_0\right)$ [€]		
	Our model	Swap model	Swap model modified
70	133 883.25	169 376.99	169 278.04
71	142 329.82	177 453.11	177 338.06
72	149 064.70	184 329.08	184 214.03
73	155 744.79	190 967.08	190 868.14
74	162 210.85	196 559.51	196 543.41
75	167 768.16	203 315.74	203 315.74
76	171 812.99	207 775.53	207 775.53
77	176 340.16	211 374.60	211 359.03
78	179 690.59	215 125.38	215 109.82
79	182 984.58	218 699.33	218 683.76
80	187 219.28	222 428.90	222 413.33
81	191 159.64	225 715.63	225 683.96
82	193 499.41	227 551.97	227 520.30
83	196 845.18	229 697.10	229 680.99
84	198 612.17	231 787.91	231 771.80
85	201 095.30	233 176.20	233 160.09
86	203 176.11	234 641.15	234 641.15
87	205 715.93	235 573.55	235 573.55
88	206 842.09	236 518.07	236 518.07
89	207 790.92	237 399.20	237 399.20
90	209 285.93	238 225.31	238 225.31
91	210 631.49	239 049.29	239 049.29
92	211 748.63	239 785.00	239 785.00
93	212 895.92	240 371.21	240 371.21
94	213 796.96	241 223.23	241 223.23
95	214 562.29	241 479.47	241 479.47
96	214 894.26	242 368.00	242 368.00
97	215 686.31	242 622.45	242 622.45
98	216 312.04	242 859.03	242 859.03
99	216 895.45	243 069.28	243 069.28
100	217 624.18	243 176.22	243 176.22

The aforementioned results are not restricted to the case of RE deployments under the RE PPA business model, as the relationship between the value of the RE system for a self-consumer, the volatility of the alternative electricity market and the cost and consumption of capital that the proposed methodology allows assessment for, is relevant to the financial appraisal of RE projects, independent of the specifications of the business model.

5. Conclusions

RE PPAs present a number of advantages that make them suited to many potential offtakers although its adoption is hampered by, among other issues, the high level of guarantees demanded by producers in order to hedge the credit risk of the project. This is caused, to a certain extent, by the fact that RE PPA credit assessment is basically determined by the credit rating of the offtaker, reflecting a lack of valuation methodologies suited to identifying and describing the credit risk generated at project level.

In order to facilitate a more comprehensive risk assessment of RE PPAs, a valuation and credit risk model are proposed, including numerical methods for its implementation. Thus, the value of an RE PPA for the offtaker, and hence the probability of default, results from potential reductions in the cost and volatility of the electricity compared to alternatively obtaining it from the electricity market. In particular, the value resulting from volatility reductions is estimated by identifying and quantifying the optionality for the offtaker embedded in the PPA at any time in relation to the electricity market. The resulting valuations reflect the specific terms of an RE PPA (price, time and amount of electricity to be delivered) and the characteristics of the electricity market price, which in the model acts as the underlying asset. The credit risk inherent to the project is then obtained by calculating the probability of default at any time, which is the probability that the value of the PPA becomes negative for the offtaker. Notice that the numerical results presented here correspond to the choice of the electricity price model and the time period of the data sample considered, although by plugging an alternative electricity price model the same methodology can be applied and similar findings are expected in the PPA valuation model.

Including the value for the offtaker resulting in the reduction of uncertainty on the future electricity costs in the credit risk assessment, is a contribution of this paper which has relevant implications on different levels. First, if an RE PPA delivers cost volatility reductions, grid parity is achieved on LCOE levels higher than the long term cost of the electricity from the market. Secondly, collateral requirements for PPAs which are in the money, or slightly out-of-the-money, might be lower than the outstanding debt, especially if the electricity market price is highly volatile and presents spikes. Thirdly, for LCOE/P_{PPA} levels sufficiently out-of-the-money, collateral requirements are independent of the specifics of the project. Nevertheless, at a given point, reductions in LCOE/P_{PPA} also result in collateral requirement reductions, fuelling positive reinforcement dynamics. This finding might be used to design supporting policies focus firstly on reducing LCOE/P_{PPA} with direct grants/subsidies to the point where collateral reductions are possible and then gradually introducing supporting tools based on guarantees, as they take hold.

In its current form, the proposed model has a number of limitations that must be considered and eventually addressed. Thus, the optional value of the PPA depends on the default windows which have been considered here to take place annually. A more realistic approach should make explicit the actual periodicity of the default windows considering relevant constraints such as the ease of switching from the PPA to the grid and the time of price revisions when obtaining the electricity from the grid. Furthermore the model assumes that P_{PPA}/LCOE has no uncertainty so all the uncertainty arises from P_t. This is not the case, in particular, if the model is used to compare the LCOE and P_t as the LCOE has also uncertainty, for example, as a result of intermittency in production and OPEX disbursement during the lifetime of the systems. Nevertheless, the proposed model can easily be adapted to include this and other technical, economic and contractual features in order to provide a useful tool for RE PPA appraisal.

CRediT authorship contribution statement

Julio Pombo-Romero: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Oliver Rúas-Barrosa:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Carlos Vázquez:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Acknowledgements

JP and OR acknowledge the funding from the European Union's Horizon2020 research and innovation program under grant agreement No 952879. CV and OR also acknowledge funding from the Galician Government (grant ED431C 2022/47, including FEDER financial support), as well as the support received from the Centro de Investigación en Tecnologías de la Información y las Comunicaciones de Galicia, CITIC, funded by Xunta de Galicia and the European Union (European Regional Development Fund, Galicia 2014–2020 Program) through the grant ED431G 2023/01. Moreover, CV and OR acknowledge the funding from the Spanish Ministry of Science, Innovation and Universities (grant PID2022-141058OB-I00). Finally, OR acknowledges the funding by the predoctoral FPI contract with reference PREP2022-000039. Authors are grateful for the comments of two anonymous reviewers that contributed to the improvement of the article.

Appendix A. Numerical methods

In order to provide the outcomes which shed some light on the PPA model, we will introduce the numerical methodologies that have been applied. In estimating the expected value of the PPA, $\mathbb{E}\left[V_{\text{PPA}}(t_k) \mid V_{\text{PPA}}\left(t_{k-1}\right) > 0\right]$, besides the underlying asset values at those times which determine the possible alternative scenarios, the general and recommended approach is to sample values at intermediary times in order to improve the accuracy of the numerical method. We denote $\tau_k = \left[t_k, t_{k+1}\right]$ the time interval between t_k and t_{k+1} for $k = 0, \ldots, M-1$, which is comprised of n time points which we will consider constant. The bigger this n is, the lower the discretization error becomes. For the present paper, we have considered $n = 0$.

Once this is clear, we must choose a model for the electricity market price and depending on whether or not it has an analytical solution, draw values from the analytical expression or the discretization scheme. The aspects related to the electricity price model choice are presented in Section 3 as well as the data sample and parameter estimation.

A.1. PPA valuation

We need to compute the expected value $\mathbb{E}\left[V_{\text{PPA}}(t_k) \mid V_{\text{PPA}}\left(t_{k-1}\right) > 0\right]$ for each $k = 0, \ldots, M-1$, and hence we start drawing N paths of the electricity market price model. Note that N must be large enough to reduce the error of the approximation. Then, for each path, the possible alternative scenarios at each time, i.e., $\left\{X_0^0, \ldots, X_{M-1}^0\right\}$, $\left\{X_1^1, \ldots, X_{M-1}^1\right\}$, …, $\left\{X_{M-1}^{M-1}\right\}$ must be calculated. The maximum of the possible alternative scenarios at each time t_k is the PPA Value at time t_k. Therefore, the expected value will become the average over the paths. The general procedure for the PPA valuation at t_0 from the viewpoint of the offtaker is depicted below.

Table B.8
Mean absolute errors of the parameter estimates obtained from averaging the calibration results of each simulated sample size over 1000 trajectories.

	Mean absolute error					
	$N_{obs} = 100$	$N_{obs} = 200$	$N_{obs} = 500$	$N_{obs} = 1000$	$N_{obs} = 2000$	$N_{obs} = 4437$
α	0.100554	0.050925	0.024475	0.013791	0.009126	0.006277
β	5.236130	3.161255	1.771568	0.828346	0.515327	0.356644
σ_b^2	0.197646	0.212008	0.086297	0.025475	0.017026	0.014519
μ_s	1.613859	1.491974	1.139736	0.768704	0.493935	0.219330
σ_s^2	0.389669	0.376024	0.299993	0.221316	0.168905	0.118389
μ_d	0.501666	0.396226	0.275379	0.200622	0.149838	0.117924
σ_d^2	0.220658	0.165373	0.088231	0.061453	0.040811	0.031312
p_{11}	0.055618	0.032609	0.015134	0.006195	0.003187	0.002109
p_{22}	0.370229	0.365179	0.239972	0.162940	0.082302	0.023883
p_{33}	0.142053	0.078632	0.034958	0.020839	0.016106	0.011745

Table B.9
Percentage changes between the quantiles and percentiles of the deseasonalized electricity market price and percentile and quantile averages over 1000 simulations for a given number of observations.

	Percentage changes [%]					
	$N_{obs} = 100$	$N_{obs} = 200$	$N_{obs} = 500$	$N_{obs} = 1000$	$N_{obs} = 2000$	$N_{obs} = 4437$
q = 0.10	13.91	7.41	3.44	2.10	1.64	1.25
q = 0.25	10.73	5.38	2.49	1.96	1.59	1.38
q = 0.50	9.77	3.87	1.17	1.56	1.79	1.92
q = 0.75	6.43	−1.22	−6.37	−6.87	−4.90	−2.74
q = 0.90	5.79	−5.24	−16.71	−23.60	−24.25	−23.10

Procedure 1 PPA Value Estimation (from t_0's point of view)

1. Given P_{t_0} and the model parameters that have been estimated, simulate N independent paths of the electricity price process with n intermediary time points between t_k and t_{k+1}

   $\{P^j_{t_0}, P^j_{t_1}, \ldots, P^j_{t_M}\} \quad j = 1, \ldots, N$

2. For each path and for $k = (0, \ldots, M-1)$ compute the possible scenarios from t_0:

   $\{X^0_0, X^0_1, \ldots, X^0_{M-1}\}$

3. Compute the maximum value for each path and take the expected value, i.e., average the maximum value of the possible scenarios over the paths.

Nevertheless, if the PPA value is evaluated at $t_k > t_0$, the procedure changes slightly because we must take into account those paths whose PPA value at t_{k-1} was negative.

Procedure 2 PPA Value Estimation (from t_k's point of view)

1. Starting from the previous algorithm.
2. Given $V^j_{\text{PPA}}(t_{k-1})$, where the superscript denotes the path j, if $V^j_{\text{PPA}}(t_{k-1}) \le 0$ then this path will not be considered in evaluating the PPA value at t_k.
3. For each valid path and for $k = (1, \ldots, M-1)$ compute:

   $\{X^k_k, \ldots, X^k_{M-1}\}$

4. Calculate the maximum value for each path and take the expected value, i.e., average the maximum value of the possible scenarios over the paths.

A.2. Default probability

As we can see from Eq. (2.11), and which has been outlined in the previous procedure, we are interested in those paths whose V_{PPA} becomes negative. Therefore, we search for and count those paths which provide a negative value for the PPA and by means of the classical definition of default probability, we calculate such probability by dividing the number of paths with the desired event by the total number of paths. Furthermore, those paths whose PPA value became negative at t_{k-1} will not been taken into account at t_k. The procedure is shown below:

Procedure 3 Default Probability

1. From t_0's point of view
   (a) Given P_{t_0} and the model parameters that have been estimated, simulate N independent paths of the electricity price process with n intermediary time points between t_k and t_{k+1}

   $\{P^j_{t_0}, \ldots, P^j_{t_M}\} \quad j = (1, \ldots, N)$

   (b) Compute the different scenarios that the PPA can have for each path starting from t_0, that is $\{X^0_0, X^0_1, \ldots, X^0_{M-1}\}$.
   (c) Given a path, if none of the scenarios provides a positive value of the PPA, then this path is a defaulting one, that is, if the maximum is negative there is a default.
   (d) Determine the number of paths with negative V_{PPA} value and apply the classical definition of probability. This is the probability of default at t_0.
2. From t_k's point of view
   (a) Given the electricity prices that have been simulated and that $V^j_{\text{PPA}}(t_{k-1})$ is known for each path j, determine that set of j's, τ, whose $V^j_{\text{PPA}}(t_{k-1}) \le 0$.
   (b) Compute the PPA values at t_k, that is, $V^j_{\text{PPA}}(t_k)$ for each path.
   (c) If $j \in \tau$ then this path is not included. Otherwise, determine whether $V^j_{\text{PPA}}(t_k)$ is negative or positive.
   (d) Take into account those j's $\notin \tau$ whose PPA value is negative and apply the classical definition of probability.

Appendix B. Calibration

In order to check the adequacy of the model, in addition to the averages of the parameters and moments for an increasing number of observations presented in Tables 2 and 3, the mean absolute error (see Table B.8) and the percentage changes (see Table B.9) between the quartiles $(0.25, 0.50, 0.75)$ and percentiles $(0.10, 0.90)$ were computed. For a number of observations equal to the number of data points, the percentage change is similar for all percentiles and quartiles except the quartile 0.75 and percentile 0.9, being this latter measure greater than the rest. The negative sign of the percentage change indicates that the value obtained from the deseasonalized electricity market is lower than the mean value over the 1000 trajectories. In this sense the calibrated model will show spikes which are greater than the observed ones.

References

Bachus, K., 2023. Risk Assessment and Geographic Impact of Virtual Power Purchase Agreements and Unbundled Renewable Energy Certificates on Greenhouse Gas Abatement (Ph.D. thesis). The University of North Dakota.

Baker McKenzie, 2015. The Rise of Corporate PPAs: A New Driver for Renewables. Technical Report, Mckenzie Baker, URL https://www.bakermckenzie.com/-/media/files/insight/publications/2015/12/the-rise-of-corporate-ppas/risecorporateppas.pdf. (Online Accessed 21 March 2023).

Baringa Partners LLC, 2022. Commercial Power Purchase Agreements. Technical Report, URL https://advisory.eib.org/publications/attachments/commercial-power-purchase-agreements.pdf. (Online Accessed 21 March 2023).

Bruck, M., Sandborn, P., 2021. Pricing bundled renewable energy credits using a modified LCOE for power purchase agreements. Renew. Energy 170, 224–235. http://dx.doi.org/10.1016/j.renene.2021.01.127.

Bruck, M., Sandborn, P., Goudarzi, N., 2018. A levelized cost of energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs). Renew. Energy 122, 131–139. http://dx.doi.org/10.1016/j.renene.2017.12.100.

Calvo-Garrido, M., Ehrhardt, M., Vázquez, C., 2019. Jump-diffusion models with two stochastic factors for pricing swing options in electricity markets with partial-integro differential equations. Appl. Numer. Math. 139, 77–92. http://dx.doi.org/10.1016/j.apnum.2019.01.001.

Carrêlo, I.B., Almeida, R.H., Narvarte, L., Martinez-Moreno, F., Carrasco, L.M., 2020. Comparative analysis of the economic feasibility of five large-power photovoltaic irrigation systems in the Mediterranean region. Renew. Energy 145, 2671–2682. http://dx.doi.org/10.1016/j.renene.2019.08.030.

Cartea, A., Figueroa, M.G., 2005. Pricing in electricity markets: a mean reverting jump diffusion model with seasonality. Appl. Math. Finance 12 (4), 313–335. http://dx.doi.org/10.1080/13504860500117503.

Crosbie, P., Bohn, J., 2019. Modeling default risk. In: World Scientific Reference on Contingent Claims Analysis in Corporate Finance. Corporate Debt Valuation with CCA. World Scientific, pp. 471–506. http://dx.doi.org/10.1142/9789814759595_0020.

Cuervo, F.I., Arredondo-Orozco, C.A., Marenco-Maldonado, G.C., 2021. Photovoltaic power purchase agreement valuation under real options approach. Renew. Energy Focus 36, 96–107. http://dx.doi.org/10.1016/j.ref.2020.12.006.

Dahlgren, M., 2005. A continuous time model to price commodity-based swing options. Rev. Deriv. Res. 8, 27–47.

Edge, P., 2015. An approximation of counterparty credit risk in long term power purchase agreements (PPAs). In: 2015 12th International Conference on the European Energy Market. EEM, IEEE, Lisbon, Portugal, pp. 1–4. http://dx.doi.org/10.1109/EEM.2015.7216645.

Freeman, J.M., DiOrio, N.A., Blair, N.J., Neises, T.W., Wagner, M.J., Gilman, P., Janzou, S., 2018. System Advisor Model (SAM) General Description (Version 2017.9. 5). Technical Report, National Renewable Energy Lab.(NREL), Golden, CO (United States).

Gabrielli, P., Aboutalebi, R., Sansavini, G., 2022. Mitigating financial risk of corporate power purchase agreements via portfolio optimization. Energy Econ. 109, 105980. http://dx.doi.org/10.1016/j.eneco.2022.105980.

Geman, H., Roncoroni, A., 2006. Understanding the fine structure of electricity prices. J. Bus. 79 (3), 1225–1261. http://dx.doi.org/10.1086/500675.

Genoese, F., Genoese, M., Wietschel, M., 2010. Occurrence of negative prices on the German spot market for electricity and their influence on balancing power markets. In: 2010 7th International Conference on the European Energy Market. IEEE, pp. 1–6. http://dx.doi.org/10.1109/EEM.2010.5558703.

Ghiassi-Farrokhfal, Y., Ketter, W., Collins, J., 2021. Making green power purchase agreements more predictable and reliable for companies. Decis. Support Syst. 144, 113514. http://dx.doi.org/10.1016/j.dss.2021.113514.

Glasserman, P., 2003. Monte Carlo Methods in Financial Engineering. Springer.

Goutte, S., Zou, B., 2013. Continuous time regime-switching model applied to foreign exchange rate. Math. Financ. Lett. 2013, 8.

Hundt, S., Jahnel, J., Horsch, A., 2021. Power Purchase Agreements and Financing Renewables: An Interdependency. J. Struct. Financ. 27 (1), 35–50. http://dx.doi.org/10.3905/jsf.2020.1.119.

Janczura, J., Trück, S., Weron, R., Wolff, R.C., 2013. Identifying spikes and seasonal components in electricity spot price data: A guide to robust modeling. Energy Econ. 38, 96–110. http://dx.doi.org/10.1016/j.eneco.2013.03.013.

Janczura, J., Weron, R., 2010. An empirical comparison of alternate regime-switching models for electricity spot prices. Energy Econ. 32 (5), 1059–1073. http://dx.doi.org/10.1016/j.eneco.2010.05.008.

Janczura, J., Weron, R., 2011a. MRS3IR_EST: MATLAB Function to Estimate Parameters of a Markov Regime-Switching (MRS) Model with 3 Independent Regimes. HSC Software, Hugo Steinhaus Center, Wroclaw University of Technology, https://ideas.repec.org/c/wuu/hscode/m11010.html. (Online Accessed 01 April 2024).

Janczura, J., Weron, R., 2011b. MRS3IR_SIM: MATLAB Function to Simulate Trajectories of a Markov Regime-Switching (MRS) Model with 3 Independent Regimes. HSC Software, Hugo Steinhaus Center, Wroclaw University of Technology, https://ideas.repec.org/c/wuu/hscode/m11011.html. (Online Accessed 01 April 2024).

Janczura, J., Weron, R., 2012. Efficient estimation of Markov regime-switching models: An application to electricity spot prices. AStA Adv. Stat. Anal. 96, 385–407. http://dx.doi.org/10.1007/s10182-011-0181-2.

Janczura, J., Weron, R., 2014. Inference for Markov regime-switching models of electricity spot prices. In: Benth, F.E., Kholodnyi, V.A., Laurence, P. (Eds.), Quantitative Energy Finance: Modeling, Pricing, and Hedging in Energy and Commodity Markets. Springer New York, New York, NY, pp. 137–155. http://dx.doi.org/10.1007/978-1-4614-7248-3_5.

Kim, K., Park, H., Kim, H., 2017. Real options analysis for renewable energy investment decisions in developing countries. Renew. Sustain. Energy Rev. 75, 918–926. http://dx.doi.org/10.1016/j.rser.2016.11.073.

Kluge, T., 2006. Pricing Swing Options and Other Electricity Derivatives (Ph.D. thesis). University of Oxford.

Lucia, J.J., Schwartz, E.S., 2002. Electricity prices and power derivatives: Evidence from the nordic power exchange. Rev. Deriv. Res. 5, 5–50. http://dx.doi.org/10.1023/A:1013846631785.

Mäntyvaara, A., 2022. Economic Characteristics of Power Purchase Agreements (Master's thesis). Aalto University.

Mendicino, L., Menniti, D., Pinnarelli, A., Sorrentino, N., 2019. Corporate power purchase agreement: Formulation of the related levelized cost of energy and its application to a real life case study. Appl. Energy 253, 113577. http://dx.doi.org/10.1016/j.apenergy.2019.113577.

Merton, R.C., 1974. On the pricing of corporate debt: The risk structure of interest rates. J. Financ. 29 (2), 449–470. http://dx.doi.org/10.2307/2978814.

Nazeran, P., Dwyer, D., 2015. Credit Risk Modeling of Public Firms: EDF9. Technical Report, Moody's Analytics, pp. 1–42.

Peña, J.I., Rodriguez, R., Mayoral, S., 2022. Modeling Renewable Power Purchase Agreements Prices. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4153205.

Pombo Romero, J., Paniego Moya, L., 2021. Economic Assessment Methodology for Photovoltaic Irrigation. Technical Report, http://dx.doi.org/10.5281/zenodo.6373415.

Red Eléctrica de España, 2022. Precio medio horario final suma de componentes. https://www.esios.ree.es/es/analisis/10211?compare_indicators=&start_date=01-01-2010T00%3A00&geoids=&vis=1&end_date=01-01-2022T23%3A55&compare_start_date=31-12-2009&groupby=day#. (Online Accessed 1 December 2022).

Source, R., 2020. Risk Mitigation for Corporate Renewable PPAs. Technical Report, URL https://windeurope.org/intelligence-platform/product/risk-mitigation-for-corporate-renewable-ppas/. (Online Accessed 03 April 2024).

Steffen, B., 2020. Estimating the cost of capital for renewable energy projects. Energy Econ. 88, 104783. http://dx.doi.org/10.1016/j.eneco.2020.104783.

Virtanen, P., Gommers, R., Oliphant, T.E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S.J., Brett, M., Wilson, J., Millman, K.J., Mayorov, N., Nelson, A.R.J., Jones, E., Kern, R., Larson, E., Carey, C.J., Polat, İ., Feng, Y., Moore, E.W., VanderPlas, J., Laxalde, D., Perktold, J., Cimrman, R., Henriksen, I., Quintero, E.A., Harris, C.R., Archibald, A.M., Ribeiro, A.H., Pedregosa, F., van Mulbregt, P., SciPy 1.0 Contributors, 2020. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nat. Methods 17, 261–272. http://dx.doi.org/10.1038/s41592-019-0686-2.

Weron, R., Kozłowska, B., Nowicka-Zagrajek, J., 2001. Modeling electricity loads in California: a continuous-time approach. Phys. A 299 (1-2), 344–350. http://dx.doi.org/10.1016/S0378-4371(01)00315-6.

Weron, R., Simonsen, I., Wilman, P., 2004. Modeling highly volatile and seasonal markets: evidence from the Nord Pool electricity market. In: The Application of Econophysics: Proceedings of the Second Nikkei Econophysics Symposium. Springer-Verlag, pp. 182–191. http://dx.doi.org/10.1007/978-4-431-53947-6_25.