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Government backed credit guarantee schemes for offtaker counterparty risk under corporate power purchase agreements

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ABSTRACT

In this study we develop a formal model that explicitly considers the cash flows of an intermittent renewable electricity producing asset backed by a corporate PPA to establish a link between the default probability of the offtaker and the PPA price needed to reach the required return on equity. In this regard, we expand the classical LCOE framework to incorporate offtaker-related credit risk. We find that offtaker defaults have a substantial impact on the PPA price and hence the LCOE of the project depending on the survival function of the offtaker. Furthermore, we propose a lean credit enhancement scheme targeting offtaker defaults based on five core principles of government involvement in infrastructure projects and credit guarantees as well as incorporate the scheme in our formal model. We compare the costs of the credit guarantee scheme with the cost of traditional support measures and find that the government may provide revenue support to renewable energy projects at a lower cost compared to CfDs. In a case study for Germany, we quantify the effect of offtaker defaults on the PPA price. For non-investment grade offtakers, the required PPA price is from 7.83 € per MWh (or 11%) up to 40.87 € per MWh (or 56%) higher than the default free price. In the case study, expected support costs for the guarantee scheme are approximately half the support costs of a comparable CfD scheme.

1. Introduction

A Power purchase agreements ("PPA") is a contract between a renewable energy producer as the seller and an offtaker as the purchaser of electricity. The offtaker can be a large utility but also any corporate consumer of electricity. PPAs with corporate offtakers play a pivotal role in the growing of age of renewable electricity generation and underpin the transition from a system backed by government support to market solutions. Governmental bodies such as BMWK (2023) and the European Commission (Zachmann, 2023) as well as industry bodies like BDEW (2023) consider PPAs an important building block of the energy transition. Baringa (2022) estimates an appetite from generators for PPAs with non-governmental offtakers of up to 480 TWh by 2030 in Europe. According to PEXAPARK (2024), the European PPA market is growing impressively with 16.2 GW capacity contracted in 2023 corresponding to a year-on-year growth rate of 41%. Corporate PPAs have become increasingly relevant with 12 GW contracted in 2023. However, only large investment grade rated corporations like Amazon, Microsoft, or Vodafone may act as offtakers under corporate PPAs due to credit risk-related concerns. The credit worthiness of corporate

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offtakers has been identified by Baringa (2022) as a clear barrier to the growth of corporate PPAs in markets in Europe. Government guarantees addressing the offtaker related credit risk are a potential way to alleviate this constraint and accelerate the deployment of PPA backed carbon free electricity production capacity. This motivates the investigation of the application of guarantees in this context. For this, we develop a general model to explore how offtaker defaults impact the price of a PPA also incorporating guarantees covering potential defaults under the PPA. Based on a case study for Germany, we provide PPA prices considering defaults associated with various offtaker rating categories and the cost of support for different guarantee specifications.

In the next subsection we will summaries the current state of the research on PPAs and related offtaker default risks and outline how this study contributes to the literature.

1.1. Current state of the literature on corporate PPAs and related credit risk and contribution of this study

As in any private contract, most elements of the PPA are the result of negotiations. Contract parties have a lot of flexibility to structure the contracts and allocate the various related risks among each other. Mendicino et al. (2019) provide an excellent overview and a comprehensive framework of the key elements of a PPA. Furthermore, Mittler et al. (2025) conducted a very thorough review of different PPA types. The key elements of PPAs include the price for the electricity produced, the volume of the energy delivered as well as the timing of delivery and the tenor of the contract. Parties may enter into baseload PPAs which leave the volume risk with the producer or pay-as-produced PPAs where volume risk is transferred to the offtaker. We consider a pay-as-produced PPA as our study is focused on offtaker default risk from the perspective of the producer and not volume risk. From a sellers perspective, the main reasons to enter into a PPA are diversification as well as stabilization of revenues to ensure bankability of their project (i.e., ability to secure debt financing). The offtaker on the other hand seeks to secure clean energy to meet sustainability and carbon emission reduction targets as well as hedge electricity prices (Mendicino et al., 2019). In a recent study, Mili and Côté (2025) determine the utility of each element of a PPA to Swiss corporations based on survey methods and confirm the reasons listed before, i.e., corporations are mostly motivated to act as offtakers under PPAs to hedge against price volatility and reduce their electricity cost as well as contribute to the energy transition. Our study expands on the above mentioned work by broadening current PPA related frameworks with insights from the literature on credit guarantees and state support in infrastructure projects.

A central element of the PPA is the price per MWh delivered. The price is usually fixed for the whole tenor of the contract. Miller et al. (2017) establish that the price of the PPA needs to be sufficient to cover the capital expenditure as well as operating and financing cost, i.e., required returns of the equity and debt providers of the project. In this regard, the equilibrium PPA price should be equal to the levelized cost of electricity (“LCOE”) of the project supplying the electricity. Vice versa, the PPA price may also be considered the cost of electricity from this specific renewable energy producer. LCOE is an established concept which has been studied intensively for renewable energy projects in the literature. See for example Shen et al. (2020) for an excellent review of concepts and approaches. In the PPA context, prior studies have looked into additional cost elements which should be considered when PPAs are priced based on LCOE. Specifically, Mendicino et al. (2019) expand the traditional LCOE scope by including costs such as market operator guarantees, grid congestion charges and energy mismatch costs. Bruck et al. (2018) on the other hand consider the impact of energy delivery limits on the LCOE and hence the PPA price. As far as we are aware, our study presents the first approach to reflect the risk of the offtaker defaulting on the LCOE and hence the PPA price. Therefore, our work significantly supplements the body of literature on LCOE in the context of PPAs as mentioned earlier.

Counterparty or credit risk significantly impacts the financing conditions of the underlying project and thus is an important element of most PPAs. Counterparty risk in the context of PPAs has been covered in the literature from various angles. Gohdes et al. (2022) use survey data including information on offtaker ratings as well as the cost of capital to quantify the impact of the credit quality of the offtaker on the financing cost of renewable energy projects in Australia’s national electricity market. Hundt et al. (2021) use data on credit default swaps of potential offtakers and a survey among lenders to establish that offtaker credit risk impacts the bankability of onshore wind projects. Alafita and Pearce (2014) consider the risk of defaults in their model for the securitization of PPAs related to residential photovoltaic projects in to asset backed securities. In contrast, our study focuses on utility scale projects with single offtaker risk rather than a portfolio of retail offtakers. Gabrielli et al. (2022) build a stochastic optimization framework to maximize the financial performance of PPAs while minimizing related risks from the perspective of the offtaker where the possibility of the producer defaulting is considered. Pombo-Romero et al. (2024) propose to estimate the probability of the offtaker defaulting under the PPA based on the value of the PPA to the offtaker in every year of the project. The default probability of the offtaker is then given by the probability of the value of the PPA being negative to the offtaker. This is an excellent approach in cases when the main source of default risk of an offtaker is the PPA or the electricity procurement strategy in general. However, the majority of corporations are mostly exposed to risks not related to the PPA which may result in a default (e.g., over-indebtedness, any form of revenue loss, litigation etc.). Additionally, like most contracts which may be subject to significant valuation changes through out the term of the contract to the respective parties, PPAs usually contain high penalties in case of early termination (e.g. §19.1 in RE-Source, 2019). By using exogenous rating classes based cumulative default curves our analyses addresses these points and provides a different perspective on this issue. In this regard, our study provides an analysis of credit risk more in line with observable contractual structures and the financial reality of most offtaker than the previously mentioned studies.

In summary, our study contributes to the existing body of literature on counterparty risk in the PPA context as the study is the first to:

- develop a formal model that establishes a relationship between offtaker defaults and the PPA price,
- model government guarantees for offtaker defaults already discussed among policy makers and practitioners,
- transfer the prevailing principles on providing credit guarantees and government’s involvement in infrastructure projects to the context of PPAs.

The next section provides an overview of the literature on the involvement of governments in private infrastructure projects and credit guarantees in general, and how related principals may be applied in the context of PPAs, as well as introduces a high-level proposal how such a scheme may be implemented. In Section 3, we develop a formal model to establish a link between offtaker defaults and the PPA price, including potential government guarantees. In Section 4 we describe the setup of our case study for Germany while the results are presented in Section 5. Section 6 concludes this study.

2. Framework for governmental guarantee scheme for offtaker defaults

In the following, we give an overview of the typical parties involved in a corporate PPA backed onshore wind project and how risk is usually shared among them. Additionally, we provide arguments for government involvement related to offtaker defaults as well as propose a high-level setup for a guarantee scheme that addresses these defaults.

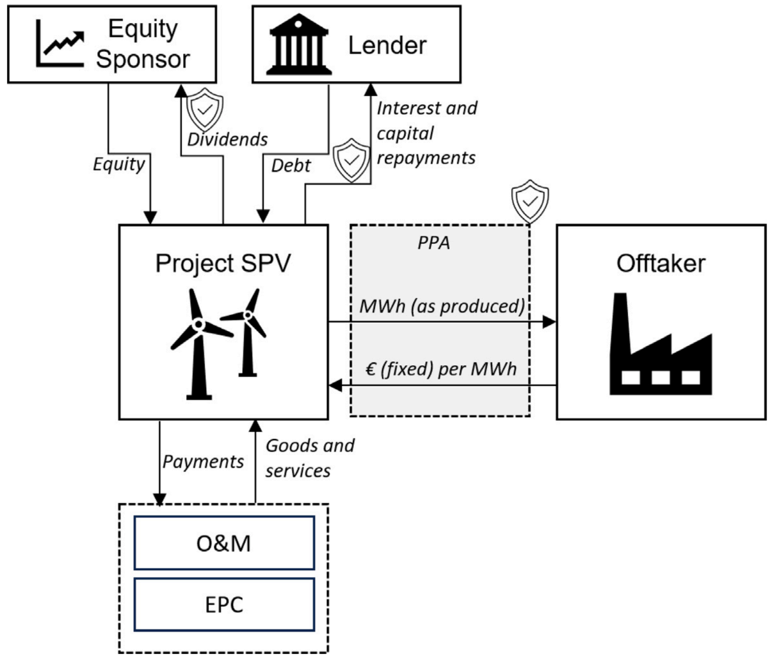


Fig. 1. Schematic overview of stakeholders involved in a typical PPA backed onshore wind project. The shield with the check mark depicts potential applications of (state) guarantees in the project. O&M is the operations and maintenance service provider and EPC the engineering, procurement and construction provider.

In Fig. 1, we present the typical project finance structure with a ring-fenced special purpose vehicle ("SPV") designated to the project. This is a typical approach to finance renewable projects, as ring fencing reduces debt overhang on the balance sheet of equity investors (Steffen, 2018). The sponsor and the lenders finance the capital expenditure of the project with equity and debt which is pooled at the level of the SPV. In return, equity and debt investors receive dividends as well as interest and capital repayments, respectively. Both appraise the project prior to providing capital and will invest only if the returns offered are adequate for the risks assumed. Usually, the construction of the project is the responsibility of a company specialized in engineering, procurement, and construction ("EPC"). Depending on the structure, the EPC may deliver the project on a turnkey basis to the project company. Operations and maintenance ("O&M") could be provided with internal resources of the SPV or contracted with a dedicated service provider. In the simplified example studied below, the total electricity production of the park is sold to one industrial offtaker for which the offtaker pays a fixed price. Mixed structures where a certain share of revenue is sold on spot markets could also be a viable option (see for example Gohdes et al., 2022).

A (public) guarantee provider is just an additional stakeholder in the project. In Fig. 1, the shield with the check mark indicates the relationships among parties that could be covered by guarantees. The focus of our research lies on the guarantee provider's involvement with the PPA and the offtaker (i.e., the bottom-right check mark).

In a project finance setup, risks should be allocated to the party most suited to bear the respective risk (Gatti, 2018). Thus, the EPC contractor should bear the risk of construction delays by a contractual obligation to reach commercial operations by a certain long stop date. Likewise, the O&M provider should bear availability risk of the asset through adequate contractual arrangements. Irwin (2007) defines the criteria for risk allocation in infrastructure projects in more detail. Risk allocation should be guided by three criteria. First, risk should be borne by the party that is able to influence the risk factor. For example, risk related to serial damages to equipment should be born by the equipment manufacturer because the manufacturer is most able to influence this risk factor by ensuring adequate quality controls throughout the manufacturing process. Second, a risk factor should be allocated to a party that influences the sensitivity of the projects' value to the risk factor (e.g., the SPV should bear interest rate risk as the sponsors and lenders decided on hedging ratios). Third, the party most able to absorb the negative impact of the realization of the risk factor should bear the respective risk. In the setup presented in Fig. 1, the risk of the offtaker defaulting is first born by the SPV and subsequently by the equity sponsor and the lender. In fact, the impact on the lender is even more pronounced, as the fixed repayment profile of the lender is immediately affected by a revenue loss related to an offtaker default. In general, the setup with only private parties is in line with the principles proposed by Irwin (2007). The equity sponsor is heavily involved in the structuring of the project, and hence also decides to enter into a PPA with a particular offtaker (i.e., influences this risk factor). Likewise, the bank will consider the offtake structure in the credit assessment of the project and approve the related risk. Furthermore, the equity sponsor influences the sensitivity of the project to the specific offtaker by choosing the share of total production contracted under the PPA. Finally, it could also be assumed that an equity sponsor should be able to bear the business risk of the project failing and that a bank with a diversified loan portfolio and adequate risk management is able to handle defaults.

Still, we argue that it is reasonable for governments to support PPA backed renewable energy projects by guaranteeing default risks for smaller offtakers with lower credit quality from a budgetary perspective and even from a welfare perspective. Regarding the latter, it could be argued that the unwillingness of banks and equity sponsors to involve offtakers with lower credit quality is due to a lack of experience with these offtakers and the absence of sufficient risk spreading as the portfolio of such projects is not large enough. In these cases of collective action friction, where not enough participants are mobilized to achieve sufficient risk spreading, Anginer et al. (2014) find that the government has a comparative advantage over markets. Hence, providing credit guarantees in these cases improves welfare. Here, state intervention can be justified to kick-start guarantee schemes that maybe overtaken by the private sector once the scheme becomes "deep enough". From a budgetary perspective, we note that the state is often already heavily involved with support schemes such as contracts for difference ("CfD") in renewable energy projects. The reason for this is that these projects need a certain "revenue quality" (Gohdes et al., 2022) to be economically feasible and that many countries support the build-out of renewable energy production to transition to a low-carbon electricity system. In this regard, a guarantee scheme has the advantage of crowding in the private sector and (as we will see in Section 5) also supports projects at lower governmental budget cost.

Overall, collective action frictions and the states current prominent role as a revenue support provider to promote the expansion of renewable energy production are sufficient arguments for the state to provide guarantees and hence credit support for offtakers. As with any government program, these credit support schemes should comply with certain standards. The literature on state support in infrastructure projects and on (government-backed) credit guarantees provides valuable insights which should be considered when designing a credit support scheme for offtaker defaults in the PPA context. Based on the review of Anginer et al. (2014), Honohan (2010), Irwin (2007), Merton and Bodie (1992) we compile five key principals. We report on these principles below and comment on their integration in the proposed PPA related scheme.

1. **Risk-based premia**: The guarantee provider should charge a premium depending on the underlying risk of the guarantee. This is mainly required to address adverse selection, which represents an inherent risk in any insurance/guarantee context (Akerlof, 1978). Ideally, guarantees should be valued by markets (Irwin, 2007). However, this is only possible if the risk or similar risks are traded. Due to the private nature of the project finance setup, market prices for default risks are generally not available (except for cases where there are traded credit instruments for the offtaker such as credit default swaps or bonds, see Hundt et al. (2021) for an application of this approach). Hence, charging risk-based premia in the PPA context requires a project specific credit assessment. Honohan (2010) suggests that the guarantee provider should only incur cost related to conducting an own credit assessment if the government has an information advantage over the other involved parties. In the PPA context, it is unreasonable to believe that the government has better information related to the default risk of the offtaker than the equity sponsor or the bank. Honohan (2010) reports on several schemes with qualified lenders, where the government relies on the credit assessment of the lenders and compliance is evaluated ex-post, penalizing non-compliant lenders. Given that only a limited number of banks are active as project finance lenders to renewable energy projects (Wind Europe, 2022 state 81 banks active in renewable energy finance in Europe) a lean ex-post evaluation approach for state credit guarantees for PPAs seems well suited. Hence, we will propose a scheme built around the concept of qualified lenders.
2. **Monitoring**: Merton and Bodie (1992) suggest that the asset underlying the guarantee should be monitored closely so that the guarantor may exercise any collateral prior to the value of the asset falling below the value of the guarantee. As with the initial credit assessment, the bank appears to be most suited to carry out the ongoing monitoring of the offtaker default risk for the guarantee provider. A corresponding duty of care of the bank could be included in the guarantee contract and likewise evaluated by the government ex-post. Currently, PPA contracts usually include requirements for the parties to report regularly on their financial situation. See for example the custom provisions of §27 of the PPA template jointly developed by the Federation of Energy Traders in Europe and the International Swaps and Derivatives Association ("ISDA") (RE-Source, 2019). In this regard, banks should be required by the guarantee terms to ensure that the SPV includes such covenants in the PPA.
3. **Deductible**: The parties which choose (i.e., the equity sponsor) and assesses (i.e., the lender) the offtaker should maintain some "skin in the game" through a deductible in the guarantee contract. This is an essential element to address moral hazard as introduced by Arrow (1978) and adverse selection . We will present various specifications of government guarantees including deductibles in our subsequent analysis.
4. **Asset restrictions**: Merton and Bodie (1992) recommend to include asset restrictions (e.g., limiting leverage) to address moral hazard. In the PPA context, this means that the offtaker has to comply with e.g., restrictions on leverage, a minimum credit rating, and/or financial covenants like interest coverage provided for in either the PPA contract or the guarantee agreement (see §26 of RE-Source (2019) for specific example provisions). Again, this is an item the involved project finance lender is well suited to implement and also monitor on behalf of the governmental guarantee provider. Hence in the guarantee scheme proposed, lenders will be obliged to implement related contractual terms.
5. **Collateral**: Merton and Bodie (1992) and Honohan (2010) stipulate that the provider of guarantees should require collateral. In the context of government guarantees for offtaker defaults under PPAs an obvious collateral is the PPA itself. Additionally, the offtaker or the project company could be required to post a cash collateral that would cover the expected loss of the guarantee (for example Pombo-Romero et al., 2024) estimate the required cash guarantees for PPAs).

In Fig. 2, we provide a high-level proposal on how a credit guarantee scheme could be designed in the context of PPAs considering the five principles mapped out before. Our proposal is based on the concept of qualified lenders that are evaluated ex-post against a risk budget. First, the government decides on a risk budget related to the intended credit guarantee scheme based on an assessment of the expected loss. This budget can only be estimated as it depends on uncertain defaults and electricity market prices (as we will see later). In this regard, the risk budget can be understood as an indication of the expected cost of the scheme. In addition, the budget is a tool to incentivize qualified lenders to provide fair information on the credit risk of the offtaker, because lenders who systematically overstate the credit quality of offtakers will receive a lower budget allocation once actual defaults exceed initial estimates. Qualified lenders are banks that meet a set of stringent requirements. The risk budget is allotted to these lenders which utilize their budget against PPA backed projects they intend to lend to and for which they need a guarantee for the default of the offtaker. The lenders are responsible for the credit assessment process for the respective projects and must provide the government with their own view of the rating of the offtaker. This rating, along with other parameters relevant to the expected loss (e.g., PPA price, volume, etc.), determines the utilization of the risk budget. Here, the government may charge a risk-based premium for providing the guarantee. The terms of the guarantee include the duty-of-care requirements of both the lender and the project SPV, i.e., lenders are required to ensure adequate monitoring of the financial situation of the offtaker and that sufficient collateral is provided (at least, the PPA needs to be pledged in favor of the guarantee provider). Whether lenders and the SPV have complied with their duty of care requirements will be evaluated in the event of default. The guarantor may terminate the guarantee if the duty of care requirements have not been met. This penalty for non-compliance is needed to address moral hazard. If a severe covenant breach occurs and/or the offtaker is permanently impaired (e.g., in case of insolvency), the lender notifies the guarantor, executes the pledged securities on behalf of the guarantor, and the guarantor steps into the PPA contract. Whether qualified lenders have provided fair information at the project selection stage will be evaluated ex-post (e.g., after five years). If defaults in the guaranteed portfolio of the respective lender are not in line with the assessment provided when the guarantee was

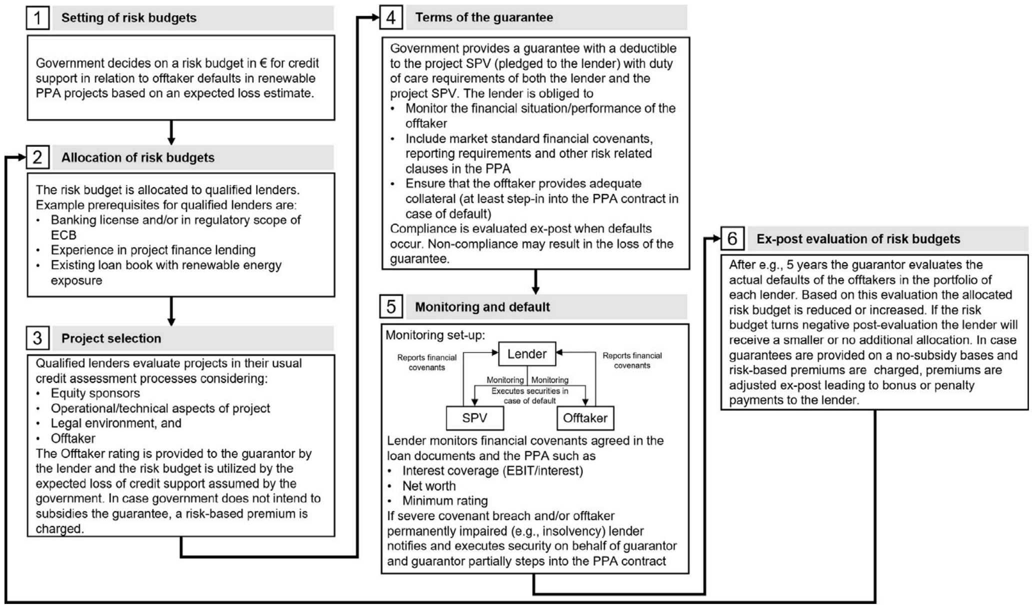


Fig. 2. High level setup for a potential credit guarantee scheme in the corporate PPA context.

issued, the risk budgets of the lender are reduced. In case risk-based premia have been charged, these could be adjusted ex-post to reflect actual risks assumed. These measures penalize lenders ex-post for not providing an accurate assessment of the offtaker default risk to the guarantee providers at the project selection stage and hence address adverse selection.

As can be seen from the above explanations, the principles from the literature on credit guarantees and the state's involvement in private infrastructure projects can be transferred appropriately to the context of guarantees on offtaker default risk and incorporated in a related governmental scheme. In the next section, we develop a formal PPA price model including offtaker defaults and subsequently expand the model to account for government guarantees.

3. Financial model of corporate PPAs including offtaker defaults

We now introduce our modeling approach to quantify the impact of offtaker default risks on PPA prices and hence the LCOE of a renewable energy project. Therefore, we look at pay-as-produced PPAs with and without governmental support over the duration of T years. For comparison, we consider a traditional LCOE based PPA price which corresponds to the PPA price without potential offtaker defaults (default free PPA price).

3.1. LCOE based PPA price

As a reference point, we introduce the widely accepted principle to price a PPA based on the LCOE of the underlying project. Following Miller et al. (2017) the LCOE, is given by

$$p_{lcoe}^{ppa} = \frac{I + \sum_{t=1}^{T} \frac{c_t \cdot (1+\Pi)^t}{(1+r_{wacc})^t}}{\sum_{t=1}^{T} \frac{E(Q_t)}{(1+r_{wacc})^t}}, \tag{1}$$

where c_t are the operating expenses, Π the inflation, I the initial investment ("capex"), r_{wacc} denotes the weighted average cost of capital and $E(Q_t)$ is the expected value of random variable Q_t with distribution function $F_t(q_t) = P(Q_t \leq q_t)$, representing the produced amount of energy in period $t = 0, \ldots, T$. The weighted average cost of capital comprises the cost of equity r_e and the cost of debt r_d, weighted by their respective shares in the overall capital structure, i.e., $\frac{e}{e+d}$ as the share of equity and $\frac{d}{e+d}$ as the share of debt:

$$r_{wacc} = r_e \cdot \frac{e}{e+d} + r_d \cdot \frac{d}{e+d}. \tag{2}$$

Please note that the inputs of Eq. (1) are exogenous and uncorrelated. In particular, the inflexible application of the cost of capital does not reflect the impact of cash flow variability and/or distribution on the project's required equity and debt returns as well as debt service capacity. As a consequence, the classical LCOE equation is not suitable to model the impact of offtaker defaults and related guarantees on the PPA price due to the offtaker defaults impact on cash flow variability. Hence, we choose to explicitly model the cash flows of the project and aim to find a pay-as-produced PPA price that provides for an adequate return on equity and interest payments for debt considering the possibility of the offtaker defaulting and potential government guarantees related to these defaults.

3.2. Explicit cash flow model including defaults

We evaluate the net present value ("NPV") of the cash flows to equity to determine the required PPA price which satisfies the return requirements of the equity provider. The NPV is a widely accepted concept in corporate and project finance and has been applied frequently in the literature to assess renewable energy assets. See for example Tsvetkova and Ouarda (2021) for a review of the application of NPVs for wind energy projects or Hürlimann (2018) for the application in renewable projects in general. The NPV is calculated by discounting the expected cash flows to equity (CFE_t for $t = 0, \ldots, T$) with the required return on equity r_e:

$$E(NPV) = \sum_{t=0}^{T} \frac{E(CFE_t)}{(1+r_e)^t} \tag{3}$$

As our model is built around Eq. (3), we provide a high level graphical representation of the central equations and how they are linked in Fig. 3. Offtaker defaults impact our model through the revenues. On the one hand, the expected value of the revenues directly influences cash flow to equity. On the other hand, revenues feed into the cash flow available for debt service ("CFADS") and the percentiles of the CFADS are central drivers of the financing cash flow. Furthermore, the volatility of

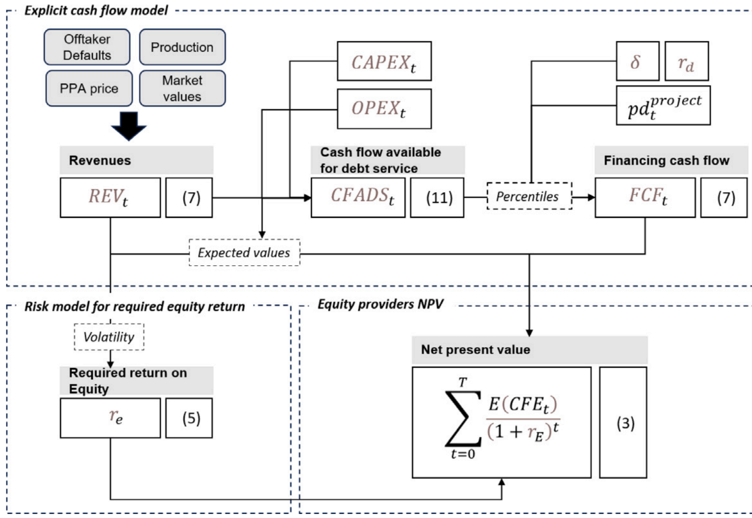


Fig. 3. High level graphical representation of central equations and how they are linked in our model. The box with the number in brackets indicates the labeling of the respective equation in the text.

revenues impacts the required return on equity, i.e., the denominator of the NPV in Eq. (3). In the remainder of this section, we expand and explain the respective equations and relationships separately in more detail.

In discounted cash flow valuation, discount rates should reflect the riskiness of cash flows (Damodaran, 2011). In valuation practice, discount rates are frequently derived through the capital asset pricing model ("CAPM"). In its initial form, the CAPM is build on a set of restrictive assumptions (Elton et al., 2009) and as a result investors are only remunerated for non-diversifiable market risk. In the application of the CAPM, discount rates are derived based on the risk free rate and regressing the asset's returns on a traded equity price index to calculate β, i.e., $E(r_e) = r_f + \beta(E(r_m) - r_f)$. In the case of non-traded assets (i.e., where no return data is available), a β is derived by calculating β for traded peers and adjusting for differences in the capital structure (Damodaran, 2011). In the case of single renewable energy projects, traded peers are usually independent power producers or renewable asset developers. These companies comprise portfolios of different technologies, construction stages, project vintages as well as offtake structures (e.g., CfD, PPA, merchant, mixed etc.). Due to the blended risk structure of the peers, a method based on traded peers is not suitable to differentiate discount rates among projects with different risk characteristics (e.g. CfD/PPA backed project vs. fully merchant project). As we will see later, this is, however, required to model the impact of offtaker defaults on the PPA price with varying guarantee coverage levels. Kitzing and Weber (2014) apply a more suitable approach by deriving β through regressing the cashflow variability of an offshore wind project on an equity price index. This allows to derive discount rates reflecting the risk drivers of a single project. However, due to the low correlation of wind production with equity prices, β derived by this method is generally close to zero for projects with a fixed price (i.e. CfDs or PPAs). Hence, derived discount rates for PPA backed projects collapse to the risk free rate, which contradicts survey data such as reported by Đukan and Kitzing (2023). To address this issue, we modify the approach of Kitzing and Weber (2014) by assuming that equity investor's utility is based on a basic mean–variance utility function, which in turn depends on the cash flow variability of the project. In a simple mean–variance utility function proposed by Elton et al. (2009) the utility f depends on the expected return and a measure of variability scaled by the risk tolerance coefficient (τ):

$$f = r_e - \frac{\sigma^2}{\tau}. \tag{4}$$

Elton et al. (2009) use the variance of returns as a measure of variability. In our application, we use the coefficient of variation ($CV = \frac{\sigma}{\mu}$) of lifetime revenue of the project ($TREV = \sum_{t=0}^{t=T} REV_t$) because this measure may be calculated from the simulated revenue path in a straight forward way and does not depend on the level of the cash flows or returns. As variance is higher when cash flows and returns are higher, applying a function based on variance would penalize projects with substantially higher returns, which is counterintuitive. Additionally, we assume that investors only go ahead with a project, if the project yields positive utility. So rearranging Eq. (4) yields a minimum return on equity r_e which depends on the variability of the underlying cash flows of the project:

$$r_e \geq \frac{CV(TREV)}{\tau}. \tag{5}$$

The cash flow to equity is determined by capital expenditure I_t (capex, only occur in $t = 0$), operating expenses c_t (opex) adjusted for inflation (Π), expected revenues $E(REV_t)$ and the financing cash flow FCF_t (i.e., debt drawdowns, repayments and interest payments). For the expected cash flow to equity CFE_t follows for period $t = 0, \ldots, T$

$$E(CFE_t) = -I_t - c_t(1+\Pi)^t + E(REV_t) + FCF_t. \tag{6}$$

To introduce offtaker defaults into our model, we assume that the project will need to sell the produced energy on a merchant basis on the spot market in case the offtaker defaults. We deem this is a realistic assumption as most PPAs include an early termination clause in case of non-performance of a party. Specifically, the template provided by RE-Source (2019) lists "failure to make payment" and "winding up/or insolvency" as causes for early termination. For our model we assume that the offtaker is permanently impaired (i.e., going through a liquidation via insolvency proceedings) and that the contract is hence terminated in case of the default. Additionally, due to the insolvency proceedings the timing and amounts of any recovery of claims related to the early termination of the PPA by the seller are highly speculative and we assume them to be zero in our model. In practice, the project's sponsors could look for a replacement offtaker. However, related cost and timing are difficult to quantify. Additionally, the pricing of the new contract will probably depend on market price expectations. In this regard, assuming that the project sells the electricity on the spot market is a reasonable and conservative baseline assumption with similar risk drivers (i.e., market price risk) as the replacement of the offtaker, while avoiding adding undue additional complexity related to quantifying search costs and pricing. Furthermore, please note that high termination penalties as provided for by §19.1 in RE-Source (2019) ensure that solvent offtakers honor PPA contracts even when they are out of the money. In other words, offtaker do not break the

PPA if the value of the contract becomes negative for the offtaker because this would result in substantial payment obligations towards the selling party/renewable energy producer. Hence, in our model, expected revenues depend on the expected revenues from the PPA and the expect merchant revenue in case of a default of the offtaker. Thus, both values have to be weighted by the survival function of the offtaker $V(t)$ i.e., the probability that the offtaker has not defaulted in t and in the periods prior to t. Revenues are thus given as:

$$E\left(REV_t\right) = V(t) \cdot p^{ppa} \cdot E\left(Q_t\right) + \left(1 - V(t)\right) \cdot E\left(P_t \cdot Q_t\right), \tag{7}$$

where P_t is a random variable with distribution function $G_t(p_t) = P(P_t \leq p_t)$, denoting the nominal market value of wind in period $t = 0, \dots, T$. Note that empirically, both random variables P_t and Q_t (i.e., the production) are usually negatively correlated as higher penetrations of wind power production in the energy mix usually depresses electricity prices due to the merit order effect (see e.g., Hirth, 2013; Ketterer, 2014; Eising et al., 2020). We use stochastic processes to simulate realizations of both time series inputs, which is further described in Section 4. Please note that we derive separate required returns on equity (r_e) for each element of the revenues to account for the differences in "riskiness" of the respective revenue stream.

The other component of the cash flow to equity is the financing cash flow FCF_t, which includes debt drawdowns and interest expenses. Interest expenses depend on the interest rate r_d and the debt balance at the beginning of the period $balance_t^{bop}$. In addition, the financing cash flow includes the scheduled repayments of the debt. Hence FCF_t is given by:

$$FCF_t = drawdown_t - r_d \cdot balance_t^{bop} - repayment_t. \tag{8}$$

Interest expenses and repayments together comprise the annual debt service of the project:

$$debtservice_t = r_d \cdot balance_t^{bop} + repayment_t. \tag{9}$$

In the project finance context debt service is usually derived by considering the cash flow available for debt service ($CFADS$) in every period and a coverage ratio ($DSCR = \frac{CFADS}{debtservice}$) as well as an externally provided maximum debt share in the capital structure (see for example Mora et al., 2019). The maximum debt share ensures that at least some of the capex is financed by equity. Lenders usually consider a downside value of $CFADS$ for the structuring of the debt service to ensure a high probability that the debt service will be met in all periods of the loan term (also termed the structuring percentile in the following). Given a certain acceptable default probability of the lenders for the project ($pd_t^{project}$) the maximum acceptable $debtservice$ per period maybe determined by the $pd_t^{project}$ percentile of the CFADS:

$$debtservice_t = max\left(\frac{CFADS_{t,p=pd_t^{Project}}}{DSCR}, 0\right). \tag{10}$$

For the sake of completeness the $CFADS$ is given as:

$$CFADS_t = REV_t - (1 + \Pi)^t c_t. \tag{11}$$

In our application, we set the $DSCR$ equal to one to maintain the explicit relationship between the debt service and the default probability of the project. In practice, the DSCR is often set to values above one to account for uncertainties not captured in the cash flow model. Please note that we consider two types of defaults in this study. First, we consider the probability of not defaulting, i.e. the survival function $V(t)$ of the offtaker, which is derived from the default probability of the offtaker under the PPA and impacts the expected value and distribution of the revenues of the project. Secondly, we consider the probability $pd^{project}$ of the project defaulting on the project debt. For our case study, we fix this $pd^{project}$ to a value corresponding to an investment grade rating so that the margin on the debt does not need to be amended. In effect, more variability in the cash flows will lead to a lower debt capacity and hence less debt while the credit margin stays the same.

Following the project finance approach, the initial debt balance at the begin of period $t = 0$, $balance_0^{bop}$, or overall debt of the project is determined by the debt service and the maximum debt share $\delta = \frac{d}{d+e}$ in the capital structure, i.e.,

$$balance_0^{bop} = \min\left(\sum_{t=1}^{T} \frac{debtservice_t}{\left(1 + r_d\right)^t}, \delta \cdot I\right). \tag{12}$$

Please note that in our case study we assume that if the $CFADS$ is negative for any period the loan needs to be repaid one period prior to this period (and consequently the loan term is adjusted). This reflects the usual constraints of lenders that interest and loan repayments should not be skipped for certain periods.

We assume the interest rate on debt to be the sum of the risk free rate r_f and the credit margin r_s, basically following a standard notation in finance (see, e.g., DeFusco et al., 2015, p. 3 or Hull and Basu, 2016, p. 524)

$$r_d = r_f + r_s, \tag{13}$$

with

$$r_s = \bar{\lambda}(1 - \beta). \tag{14}$$

Above, β represents the recovery rate and $\bar{\lambda}$ the projects average hazard rate. Assuming the worst case, that is, $\beta = 0$, the equation simplifies to $r_d = \bar{\lambda}$. In this regard, the credit spread of the project can theoretically be derived based on the default probabilities of the project. Empirically, however, observed credit spreads generally exceed actual expected losses when considering risk neutral default probabilities (Amato and Remolona, 2003), that is, default probabilities derived from bond prices are substantially higher than observed probabilities of default published regularly by the large international credit rating agencies (see, for example S&P Global, 2023 or Moody's, 2023). Thus, for our simulation study in Section 4, we fix $pd_t^{project}$ to a value corresponding to an investment grade rating and apply a credit spread in line with the assumptions of Fraunhofer ISE (2024).

The equations provided above can be solved for p^{ppa} by setting the NPV (Eq. (3)) to zero and considering the expected revenues and the structuring percentile of revenues in the cash flow to equity. You may find the detailed steps in Appendix B. Please note that to improve readability variables referring to the structuring percentile ($pd_t^{Project}$) are denoted with a hat (that is, the debt service is determined by $\widehat{CFADS}$, depending on $\hat{q}_t$ and $\widehat{q_t p_t}$ etc.). Additionally, large letters refer to vectors containing the respective variables from $t = 0, \dots, T$.

Solving for p^{ppa} gives a collection of NPVs (see the equation in Box I). Eq. (15) provides valuable insights on the factors that impact the price of the PPA given the assumptions of our model.

- Ceteris paribus higher expected market revenues $E(P \cdot Q)$ decrease the required PPA price. If the expected merchant revenue related NPV together with the merchant revenue related terms in the FCF exceed the NPV of the cost, the PPA price in Eq. (15) could theoretically be negative. In this case, of course, investors would not consider entering into a PPA. In other words, merchant revenues are sufficient to cover the costs of the project. Please note that due to our modeling approach, higher cash flow variability in merchant revenues reduces the value contribution from this revenue stream due to (i) a higher discount rate and (ii) lower values of the structuring percentile. As a result, a PPA could still be the preferred option, even if $E(PQ) > E(Q) \cdot p^{ppa}$ (i.e., expected market revenues larger than expected PPA revenues) given the impact from $r_e^m > r_e^{ppa}$ and $\hat{Q} \cdot p^{ppa} > \widehat{PQ}$.
- Generally, we can assume that the NPV based on r_d exceeds the NPV based on r_e^{ppa} because debt only adds value and improves the return of the equity investor if $r_e^{ppa} > r_d$. Given this relationship, it is obvious why the initial approach from Kitzing and Weber (2014) where r_e^{ppa} collapses to the risk free rate is not suitable

$$p^{ppa} = \frac{NPV(r_d, Cost) - NPV\left(r_e^m, (1-V)\cdot E(P\cdot Q)\right) - NPV\left(r_d, (1-V)\cdot \widehat{P\cdot Q}\right) + NPV\left(r_e^{ppa}, (1-V)\cdot \widehat{P\cdot Q}\right)}{NPV\left(r_e^{ppa}, V\cdot E(Q)\right) + NPV\left(r_d, V\cdot \hat{Q}\right) - NPV(r_e^{ppa}, V\cdot \hat{Q})} \tag{15}$$

Box I.

for our application. Investors would not include debt in the investment otherwise. Hence, a higher percentile of the merchant revenue $\widehat{P\cdot Q}$ and production $\hat{Q}$ will decrease the PPA price.

- A higher survival probability of the offtaker increases the denominator and hence reduces the PPA price. This effect is partially offset by lowering the impact of merchant revenue on the numerator. The PPA price approaches the default free price when V approaches one.
- On the other hand, if the survival function approaches zero, the denominator will also approach zero and the PPA price will theoretically approach infinity. At the same time, the positive impact from the terms in the numerator is limited to the merchant revenues.

We demonstrate the behavior of our model for different assumptions on the expected merchant revenue with a numerical example. The results of the example are displayed in Fig. 4. For the numerical example we assume that merchant revenue and capacity factors follow a simple log normal distribution. We employ a log normal distribution to also capture the impact of varying the expected merchant revenue on the variability and percentiles of the merchant revenue. We vary the expected merchant revenue and derive a PPA price based on Eq. (15) and compare this price to the excepted capture price (displayed in the left panel of Fig. 4) that forms the basis of the merchant revenue. Additionally, we plot the NPVs of the PPA and the merchant revenue in the right panel of Fig. 4. The dotted lines represent the evaluation with considering the impact of the volatility of the cash flows on the discount rate (i.e., $r_e^m > r_e^{ppa}$). The dashed lines represent the results without the impact of volatility (i.e., $r_e^m = r_e^{ppa}$).

As expected, higher capture prices decrease the required PPA price (left panel). At a certain capture price the NPV of the merchant revenue exceeds the NPV of the PPA revenue, the respective lines in the right panel of Fig. 4 cross and the merchant case becomes more attractive than the PPA case. Without considering the impact of volatility on the discount rate this is the case when the expected capture price exceeds the required PPA price (around €74 per MWh). However, if the impact of cash flow volatility is considered, substantially higher capture prices of around €200 per MWh are required to compensate for the lower economic value of the more volatile cash flow as captured by the higher discount rate r_e^m.

3.3. Comparison to expected loss based approaches

We have introduced our modeling approach which captures the impact of credit risk on the required PPA price through the revenue distribution in the prior sections. However, credit risk in derivatives and bonds, as well as project finance transactions is frequently measured through the concept of expected loss (Hull and Basu, 2016; Gatti, 2018). Hence, we discuss the relationship of our novel approach and the more traditional expected loss based approach below.

In general, expected loss is defined as the loss of an economic value (e.g., payments such as amortization, coupons, dividends etc.) weighted by the probability of the occurrence of the loss. In the context of credit risk and PPAs, the concept of expected loss has been applied by Pombo-Romero et al. (2024) and Edge (2015). We do not explicitly calculate expected loss in our approach to determine upfront cash guarantee costs as for example done by Pombo-Romero et al. (2024). In effect, however, our approach does consider expected losses in the PPA price by weighting expected economic values with the respective default probabilities. The similarity is apparent, when we rearrange the revenue components in the NPV of the CFE as given by Eq. (3) to:

$$NPV(REV) = p^{ppa}\cdot NPV(r_e^{ppa}, E(Q)) - [(1-V)\cdot(p^{ppa})\cdot NPV(r_e^{ppa}, E(Q)) - NPV(r_e^m, E(PQ))] \tag{16}$$

In Eq. (16) term in the square brackets which represents the probability weighted difference or loss related to the default may be considered the expected loss for the equity provider. As these terms form an integral part of our model expected loss is reflected in the PPA price derived. Furthermore, we consider not only expected losses, but also the variability and downside risk of cash flows via the explicit modeling of the equity providers discount rate and the structuring percentiles of the debt providers. In this regard, our model may be considered an expansion of the traditional expected loss approach, also incorporating unexpected loss and volatility.

3.4. Optimization based solution of the model

Due to the non-linearity in determining the $debtservice_t$ and subsequently the $balance_0^{bop}$ (i.e., loan term truncated if $\widehat{CFADS}$ negative), we use the optimization procedure described in Fig. 5 to derive the respective PPA prices. This is required as $\widehat{CFADS}$ may become negative. For consistently positive $\widehat{CFADS}$, the procedure described in Fig. 5 and Eq. (15) yield the same results. The steps of the procedure are as follows:

1. Derive the distribution of $CFADS_t$, i.e., the operating cash flow, for every period $t = 1,\dots,T$ based on Eq. (11).
2. Derive the financing cash flow by executing the following steps: Choose the default probability $pd_t^{project}$, $t = 1,\dots,T$ which determines the percentile of the $CFADS_t$ distribution used to derive the potential debt service per period according to Eq. (10) and determines the credit spread r_s on the risk free rate. The initial debt balance or overall debt of the project is determined by Eq. (12). The maximum debt share δ is set externally to ensure that a minimum amount of equity is invested in the project. In practice values around 80% are common for δ (e.g., Đukan and Kitzing (2023) report a debt share of 85% for Germany based on survey data, Fraunhofer ISE (2024) use a debt share of 80% in their calculations while Wind Europe (2022) report a debt share between 70%–80% for wind projects in Europe). Based on the initial debt balance the interest expenses $r_d \cdot balance_t^{bop}$ are calculated. The residuum of the $debtservice_t$ given by Eq. (9) determines the $repayment_t$ in that period. Consequently, the next period's debt balance is determined by $balance_t^{bop} - repayment_t$.
3. Based on the financing cash flow and the operating cash flow determined in steps 1 and 2 as well as the capital expenditure the cash flow to equity is derived.
4. The required return on equity is derived based on Eq. (5) considering the revenue variability.
5. Last the NPV is calculated. If the NPV is not equal to zero, the PPA price is amended accordingly.

Through the procedure described in this section, we have established a relationship between the offtaker default probability and the PPA prices. We now introduce a credit support scheme for offtaker defaults in the model to account for government support mechanisms.

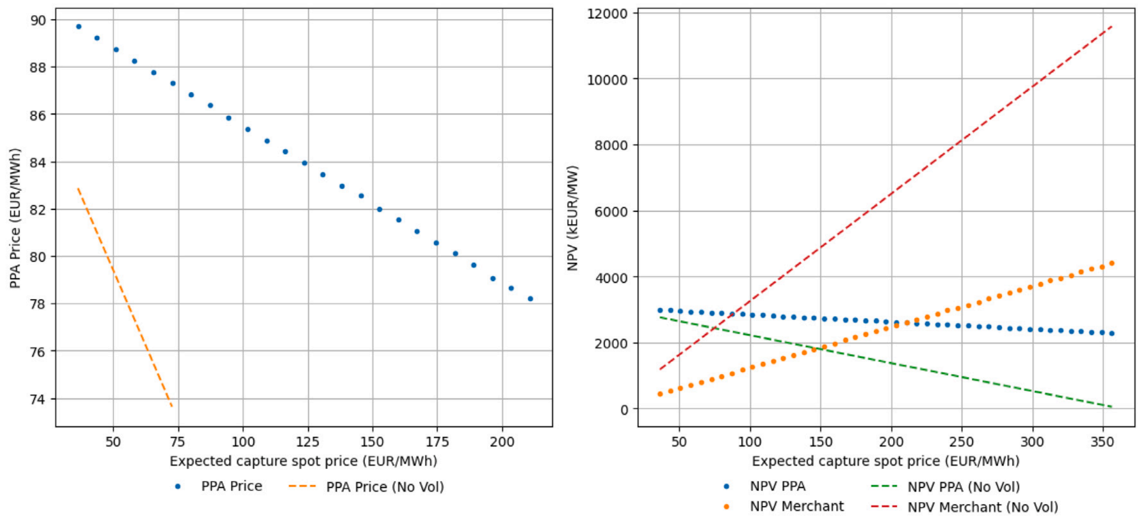


Fig. 4. Results of the numerical example to demonstrate the behavior of the model for varying expected merchant revenues. Expected merchant revenues and capacity factors are assumed to follow a lognormal distribution. Other model inputs are the same as in our simulation study (displayed in Table 2). The variance is derived from the data used to calibrate the model described in Section 4. The BB– cumulative survival curve is applied. Please refer to Appendix A for further details on the survival curves. Dotted lines represent the results where $r_e^m > r_e^{ppa}$. Dashed lines represent results where $r_e^m = r_e^{ppa}$.

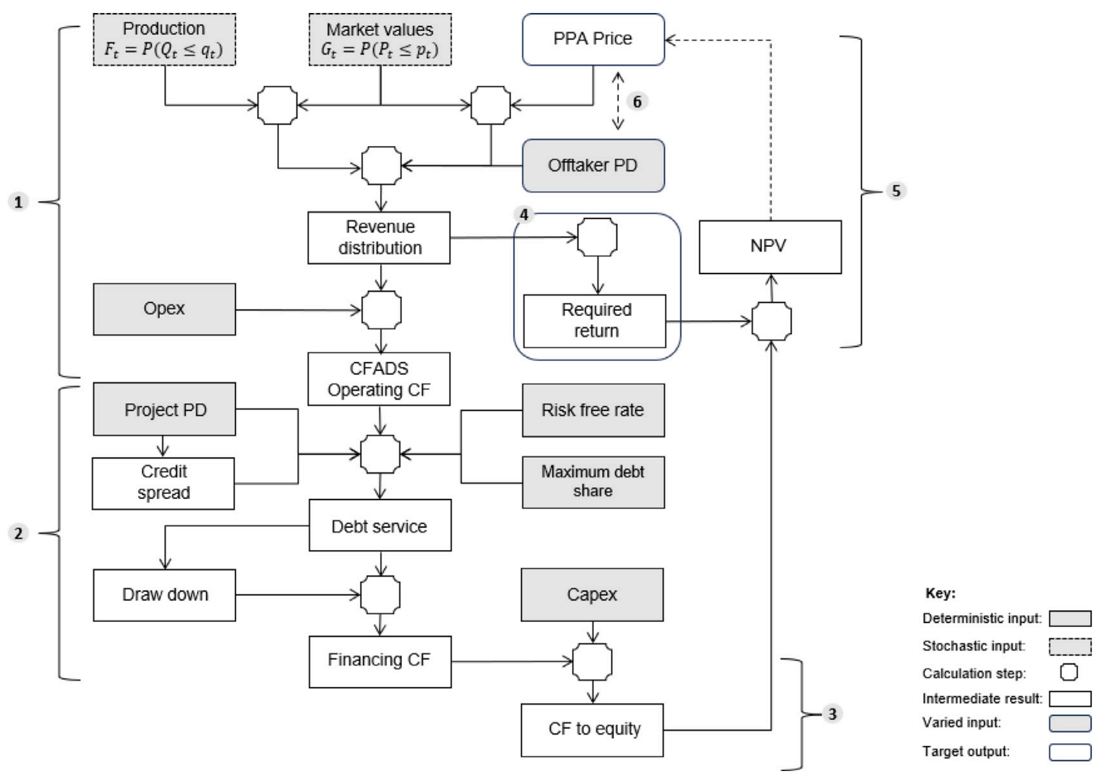


Fig. 5. Description of the steps of the optimization procedure to establish a relationship between the probability of the offtaker defaulting (Offtaker PD) and the PPA price. In step 1 the distribution of the $CFADS$/operating cash flow is derived. In step 2 the financing cash flow is determined. In step 3 the cash flow to equity is derived. In step 4 the required return on equity is derived based on the variability of revenues. In step 5 the NPV is calculated. If the NPV is not equal to zero the PPA price is amended accordingly. The procedure establishes a relationship between the Offtaker PD and the PPA price (step 6).

3.5. Model with government support

In this section, we introduce a credit guarantee mechanism into our theoretical model and derive the related cost of support. However, first, we introduce the benchmark cost of support against which we evaluate the credit guarantee mechanisms.

For our benchmark, we assume that the government supports the project from day one covering the LCOE of the project through a CfD. CfDs are a common tool for providing revenue support to energy producers. See, for example, Beiter et al. (2024) for an excellent introduction and outlook on the role of CfDs as a state-of-the-art support mechanism. The cost of support for a simple, straight forward CfD are given by:

$$costof\,support = \sum_{t=1}^{T} \frac{\left(P_t - P_{lcoe}^{ppa}\right) \cdot Q_t}{(1 + r_{social})^t}, \tag{17}$$

where r_{social} is the discount rate used by the European Commission to quantify cost and benefits of policy measures. Note, that Đukan and Kitzing (2023) apply these discount rates as well in their analysis of CfD support cost.

For the credit guarantee mechanism, we assume that the government steps in as an offtaker for a share of the production Γ in case the offtaker defaults. The price the government pays is set to the default free PPA price (P_{lcoe}^{ppa}). In this case the cost of support is given by:

$$costof\,support = \sum_{t=1}^{T} \frac{\left(1 - V(t)\right)(P_t - P_{lcoe}^{ppa}) \cdot Q_t \cdot \Gamma}{(1 + r_{social})^t}. \tag{18}$$

The coverage of the guarantee Γ may be set to a value between zero and one. Hence $(1 - \Gamma)$ represents the deductible, i.e., the "skin in the game" of the equity provider and the lender in line with principle three introduced in Section 2. Further note that we will consider the cost of support as given by Eq. (18) as a risk-based premium in the simulation study conducted later in line with principal one. Form the project's perspective this type of guarantee changes the expected revenues of Eq. (7) to:

$$E\left(REV_t\right) = V(t) \cdot p^{ppa} \cdot E\left(Q_t\right) + \left(1 - V(t)\right) \cdot \left(E\left(P_t Q_t\right) \cdot (1 - \Gamma) + (\Gamma \cdot p_{lcoe}^{ppa}) \cdot E(Q_t)\right) \tag{19}$$

Considering these guarantee payments in the steps to solve for the PPA price as done in Appendix B will result in a fairly cluttered expression. However, the impact of these payments on the PPA price is easily understood considering Eq. (15). As the guarantee payments are made only in case of default, the payments will impact the second, third and fourth expressions of the numerator only. A higher coverage will reduce the volatility of the revenues in case of default and hence the r_e applied in the calculation of the NPV. This, in turn, will reduce the required PPA price. Additionally, a higher coverage will reduce the PPA price by lifting the structuring percentile as the impact of volatility from market price movements is reduced. Later, in the case study provided, we will see how the coverage level and the r_e interact with each other and how this impacts the required PPA price. In the next two sections, we will demonstrate the application of the model in a case study.

4. Setup of simulation study

We now present the setup of our simulation study. We first describe the methodology to simulate the stochastic inputs for our model, i.e., market values of onshore wind and wind power capacity factors. Then, we specify the parameters and simulation settings used.

4.1. Market value and capacity factor simulation model

To simulate the income of the project, stochastic simulations of wind capacity factors are needed. Additionally, in the case that an offtaker defaults, the related market values are required to calculate the income in the merchant case. Thus, we model the wind market values using a simple form of a mean-reverting Ornstein–Uhlenbeck ("OU") process, commonly used for modeling electricity prices and commodity prices; see, e.g., Schwartz and Smith (2000), Fred Espen Benth and Meyer-Brandis (2007), Hayfavi and Talasli (2014), Kitzing and Weber (2014). Note that since the focus of the paper is not on advanced modeling of electricity prices and wind production, we use a rather straightforward simulation model. Thus, the monthly market value of wind P_t is simulated by using the following stochastic differential equation ("SDE"):

$$dP_t = \theta_P\left(\mu_P(t) - P_t\right)dt + \sigma_P dW_t^P, \tag{20}$$

where

- θ_P is the rate of mean reversion
- $\mu_P(t)$ is the long-term mean of prices which may vary over time
- σ_P is the volatility of the process
- dW_t^P is a Wiener process (Brownian motion).

The initial parameters θ_P, μ_P, and σ_P of the process are fitted on historic values using a Maximum-Likelihood estimation. To account for the increasing uncertainty regarding the long-term mean of prices, we increase the volatility σ_P of the process by 0.25% per month. The resulting price paths reflect our limited knowledge of prices, especially in future years where no liquid products are tradable yet. Please note that we used data only up to 2022 to avoid incorporating the exceptional market conditions during the European electricity market crisis, which could lead to unrealistic simulations. The applied model is a simplified version of the one first introduced by Schwartz and Smith (2000), where an excellent introduction to this kind of stochastic processes is also given. For the sake of brevity, we waive a deeper discussion of this theoretical topic here. For readers interested in theoretical introductions to stochastic processes for modeling commodity and electricity prices, we refer to Cont and Tankov (2003), Øksendal (2000), Tsay (2010), Aas and Dimakos (2004).

For wind capacity factors, we use a correlated Cox–Ingersoll–Ross ("CIR") process, which is a slightly amended OU-Process to avoid negative values. The CIR process is described by the following SDE:

$$dC_t = \theta_C\left(\mu_C(t) - C_t\right)dt + \sigma_C\sqrt{C_t}dW_t^C \tag{21}$$

where:

- θ_C is the rate of mean reversion,
- $\mu_C(t)$ is the long-term monthly mean for wind capacity factor,
- σ_C is the volatility coefficient, and
- dW_t^C is a Wiener process (Brownian motion).

By scaling with the current level of C_t, the CIR process avoids negative values for C_t, which seems to be better suited for capacity factors. If a negative value still appears by chance, we manually set this to 0. This process is also fitted by using a Maximum-Likelihood approach.

Note that both processes are correlated via the correlation coefficient ρ, which specifies the correlation of the Wiener processes dW_t^P and dW_t^C fitted in historical data. The resulting discrete-time versions of these equations for simulation purposes are as follows:

$$P_{t+\Delta t} = P_t + \theta_P\left(\mu_P(t) - P_t\right)\Delta t + \sigma_P\sqrt{\Delta t}\varepsilon_P,$$

$$C_{t+\Delta t} = C_t + \theta_C\left(\mu_C(t) - C_t\right)\Delta t + \sigma_C\sqrt{C_t}\sqrt{\Delta t}\varepsilon_C,$$

where ε_P and ε_C are correlated random variables such that:

$$\mathbb{E}[\varepsilon_P\varepsilon_C] = \rho.$$

4.2. Parameters

In this section, we describe all inputs required for the simulation and subsequent evaluation of the financial model introduced earlier.

The long-term mean $\mu_P(t)$ of the market values is derived from projections of the long-term price of electricity. For the first five years, starting with price simulations for 2025, we used baseload prices from European Energy Exchange (EEX) (2024), as shown in Table 1. For subsequent years, we rely on estimates provided by the Ifo Institute for Economic Research (Mier, 2023) up to the year 2040. Afterwards, we perpetuate the last available estimate. Note that these prices are in a similar range as long-term price estimations from other sources (see e.g., Gierkink et al., 2022 or Energy Brainpool, 2024). We calibrate these long-term price estimates with a capture rate of 80% for onshore wind in Germany to simulate market values. For capacity factors, we use the hourly production data provided by SMARD (2024) divided

Table 1
Historical and future long-term baseload price (estimations) of Electricity Prices (2015–2050).

Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Price (€ per MWh)	31.45	28.20	32.87	43.26	36.64	29.51	93.36	230.57	92.29	70.00	88.25
Year	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Price (€ per MWh)	84.65	76.32	70.34	68.58	67.30	68.13	66.57	67.07	66.77	68.00	67.50
Year	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Price (€ per MWh)	67.00	66.50	66.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00	65.00
Year	2048	2049	2050								
Price (€ per MWh)	65.00	65.00	65.00								

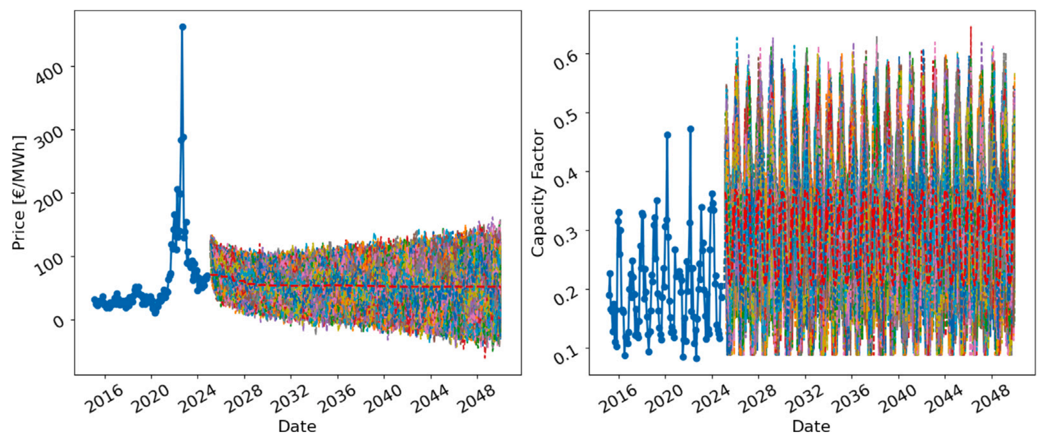


Fig. 6. Simulated onshore wind market values and capacity factors. The assumed long term average for both elements is given by the dashed red line, while the colored lines represent single simulation paths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by the (interpolated) biannual capacities for onshore wind published by WINDGUARD (2024). As there were no biannual capacities available for June 2024, we roll forward the year-end value for 2023 to calculate the capacity factors between January and October 2024. Furthermore, we scaled historical capacity factors to modern wind technologies by shifting the mean to current mean capacity factors reported by IRENA (2024) for Germany. The resulting simulations are depicted in Fig. 6 and a short visual analysis of the correlations is given in Appendix D. We annualized the monthly values for the application in the financial model.

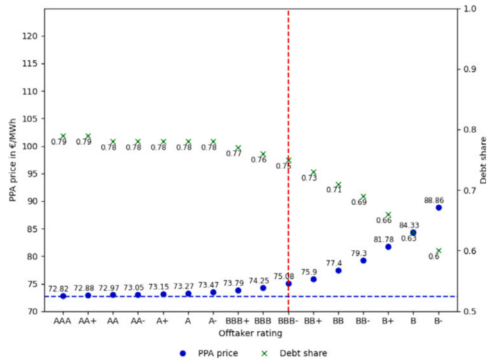
Further static technical and financial inputs are based on IRENA (2024) and Fraunhofer ISE (2024) and are given in Table 2. Please note that we have fixed the average probability of default of the project to 0.05%, which roughly corresponds to a rating category of A+. By fixing the probability of default of the project, we can also fix the interest margin of the project. In this regard, greater variability in the cash flows of the project does not result in a higher margin but in less debt provided due to the structuring approach described in Section 3.

We calibrate the risk tolerance coefficient needed to derive the respective required returns on equity in the following way. First, we assume that the r_e provided by Fraunhofer ISE (2024) represents the return requirements for a project without default risk and a fixed price (r_e^{ppa}). Second, we use our simulated capacity factors and the default free PPA price (p_{lcoe}^{ppa}) to generate revenue paths. In the third step, we calculate the CV of the generated revenue paths. Finally, we plug this CV and r_e^{ppa} into Eq. (5) and solve for τ. Please also refer to Appendix C for additional details on the required steps.

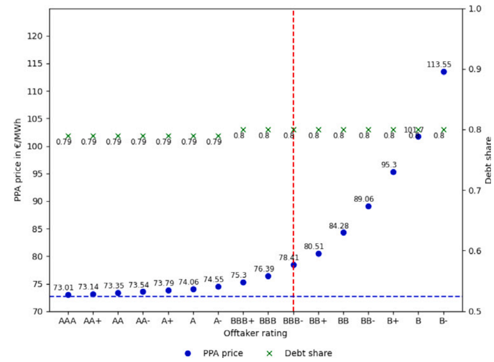
We derive the survival function per rating category from the stylized cumulative default probabilities provided by Scope Ratings GmbH (2019). These cumulative default probabilities have been constructed based on historical data amended to preserve key properties of cumulative default probability curves such as no intersection between rating categories, increasing marginal default rates for the investment grade rating category, and decreasing marginal rates for the non-investment grade category. We choose these cumulative default probability curves because these stylized curves do not suffer from the data inconsistency issues of purely empirical curves provided, for example, by S&P Global (2023), Moody's (2023). As defaults are actually quite rare events (S&P Global, 2023 report an average of nine defaults per year in Europe between 1991 and 2022), empirical data are heavily affected by outliers which result in data inconsistencies such as a rating category actually exhibiting a higher default probability than ratings below that

Table 2
Static model inputs for technical and financial assumptions. Technical model inputs are adapted from IRENA (2024) and converted from USD to EUR using an average EUR/USD exchange rate of 1.08 for 2023. Inflation corresponds to the European Central Bank's long-term target. Financial inputs are adapted from Fraunhofer ISE (2024), where the sum of the risk-free rate and the debt margin equals r_d. $pd_t^{Project}$ corresponds to an A+ rating. τ derived based on simulated revenue paths for a default free, fixed price project assuming r_e^{ppa} as provided by Fraunhofer ISE (2024).

Assumption	Value and unit
Capex (I)	1,620,400 € per MW
Opex (c_t)	49,163 € per MW
Expected capacity factor ($E(Q_t)$)	0.29
Project term (T)	25 years
Inflation (π)	2.0%
Loan term (T)	25 years
Risk-free rate	2.0%
Debt margin	3.5%
Required return on equity (r_e^{ppa})	7.0%
Risk tolerance coefficient (τ)	0.2185
Probability of default project ($pd_t^{Project}$)	0.05%
Maximum debt share (δ)	80% of I



(a) No impact of cash flow variability on r_e



(b) With impact of cash flow variability on r_e

Fig. 7. PPA prices and debt shares resulting from the procedure described in Fig. 5 for different offtaker ratings associated with the cumulative default probabilities displayed in Appendix A. The horizontal dashed blue line depicts the default free PPA price. The vertical dashed red line depicts the last investment grade rating category. The left panel 7(a) shows the values without and the right panel Fig. 7(b) with considering the impact of cash flow variability on r_e.

category. The cumulative default probabilities used in our study are shown in Fig. A.10 in Appendix A. As you may have noted, our input parameters are mainly based on market and production data for the German bidding zone as well as industry studies. In this regard, we do not simulate an asset at a specific location in Germany, but rather what could be considered an "average" wind farm. In our view, this approach is appropriate to demonstrate the functionality of our model and gain valuable insights into the impact of offtaker defaults and related guarantees on German onshore wind projects in general. In the next section, we will present the simulation results based on the procedures and model inputs derived before.

5. Results of the simulation study

In this section, we present PPA prices as well as expected cost of support resulting from our simulation procedure. In doing so, we consider offtaker default probabilities associated with different rating classes and guarantees with different coverage levels (Γ).

5.1. PPA prices considering offtaker defaults

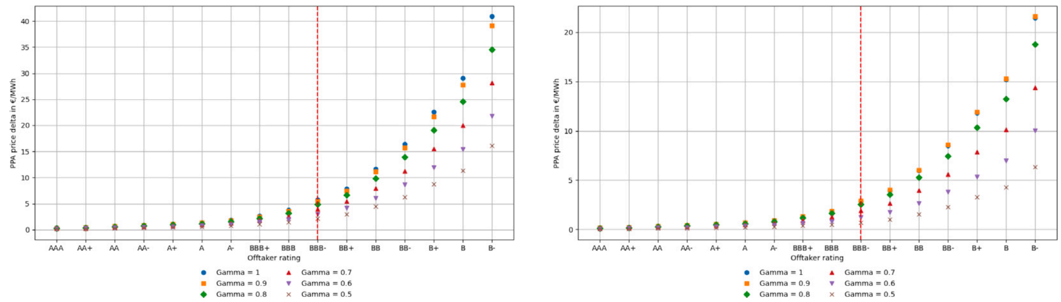
First, we derive PPA prices by running the optimization procedure described in Fig. 5 considering different survival functions associated with various offtaker ratings. Fig. 7 displays the PPA price needed to reach the required return on equity considering defaults as well as the default free PPA price of 72.68 € per MWh based on Eq. (B.6). The left panel depicts the results with a fixed r_e of 7.00%. The right panel displays results of a simulation considering the impact of cash flow variability on r_e as given by Eq. (5). The default free PPA price is in line with the higher end of the recent bids for state backed feed-in-tariffs in Germany, which were between 69.3 and 73.5 € per MWh (BNetzA, 2024) and the LCOE range for onshore wind reported by Fraunhofer ISE (2024). In this regard, our approach leads to results which are comparable to other research and with observed price points indicating an adequate specification of the model.

As expected, the impact of considering potential offtaker defaults on the required PPA price is negligible for high investment grade categories (AAA to A−) as the required price is less than one € per MWh higher than the default free price in both cases, i.e., with and without considering the impact of cash flow variability on r_e. The impact of potential offtaker defaults on the required PPA price becomes more pronounced for lower investment grade ratings (BBB+ through BBB−) with the price associated with the last investment grade rating category exceeding the default free price by 2.25 and 5.64 € per MWh, depending on the case. For non-investment grade rated offtakers the effect of defaults is significantly stronger with a steep increase of PPA prices. Furthermore, for these rating categories, the impact from the higher required return due to the increasing cash flow variability is substantial and PPA prices considering the impact of cash flow variability are between 4.61 (for BB+) and 24.69 (for B−) € per MWh higher than prices without considering cash flow variability. Please note that we do not show the prices for the lowest non-investment grade ratings which are "vulnerable to nonpayment" as defined by S&P Global (2024) in Fig. 7 due to the scale of the diagram. The values for the case with considering cash flow variability are provided in the first column and last three rows of Table E.4 and are well above 200€ per MWh for CCC and 4000 € per MWh for C rating categories. The values for the case without considering cash flow variability may be accessed through the online material published on GitHub through the link provided in the Appendix. The extreme PPA prices are the result of the very steep cumulative default curves in these rating categories with cumulative default probabilities as applied by Scope Ratings GmbH (2019) reaching 100% by year two for a rating of C and by year seven for a rating of CC. For the CCC category the cumulative default probability already exceeds 50% after year four. For theses rating categories the PPA price needs to compensate for the shortfall between the LCOE of the project and the expected market value in just a few early periods. Please also refer to the effects described in connection with the PPA price given by Eq. (15) in Section 3 (i.e., denominator approaching zero and PPA price infinity when the survival function approaches zero).

We display the debt share in Fig. 7 post-optimization (i.e., after the PPA price is increased to reach the required rate of return).The debt share declines to 0.61 for lower rating categories when r_e is fixed. When r_e rises with cash flow variability the debt share remains flat around 0.80 the maximum allowed debt share. This is explained by the optimization procedure employed to derive the PPA prices. The PPA price is adjusted until the NPV of the CFE is equal to zero. An increase in price directly impacts the NPV through expected revenues and indirectly through the FCF by lifting the $CFADS$ structuring percentile. However, the effect through the FCF is less pronounced because debt only improves the CFE through shifting payments to later periods. In the case where cash flow variability impacts r_e, higher price increases are required as in the case where cash flow variability does not impacts r_e. In effect, due to the higher required price increases and their respective impact on the $CFADS$, higher debt shares are reached in the case where cash flow variability impacts r_e.

5.2. PPA prices for various guarantee coverage levels

Next, we introduce a guarantee mechanism as described in Section 2 into the simulation. For this, we simulate various coverage levels Γ



(a) Without considering risk-based premia

(b) With considering risk-based premia

Fig. 8. Reduction of required PPA prices for various guarantee coverage levels considering the impact of cash flow variability on r_e. The left panel depicts values without considering risk-based premia. The right panel depicts values considering risk-based premia. Here, risk-based premia are reflected as an upfront payment corresponding to the discounted cost of support as given by Eq. (18).

between one and 0.5. Here it is worth noting that from the equity and debt providers perspective, $1 - \Gamma$ represents a deductible in line with principle three for providing credit guarantees as introduced in Section 2. Overall, a lower coverage means a higher deductible and hence more "skin in the game" for the equity investors and lenders.

The results of the simulation are displayed in Fig. 8. Here, we plot the price reduction per MWh compared to a case without a guarantee for different coverage levels. Please note that we consider the impact of cash flow variability on r_e in both cases. You may find the actual prices in the Tables E.4, E.5, E.6 and E.7 in Appendix E. The left panel 8(a) shows the result without considering risk-based premia. In this case, the guarantee is provided by the government free of charge and hence represents a subsidy. The right panel 8(b) provides the price reductions considering risk-based premia. Here, we have deducted the discounted cost of support as given by Eq. (18) as an upfront expense in the cash flow model. In this regard, the setup for the simulation results shown in the right panel adheres to principle one (Risk-based premia) of Section 2.

Obviously, the price reduction related to government guarantees is negligible for offtakers with high investment grade ratings because the impact of defaults on the PPA price is very low for these rating categories in the first place. We can observe a moderate impact on the PPA price from government guarantees for lower investment grade rated categories in the BBB range. For non-investment grade rated categories, i.e., to the right of the vertical dashed red line, in Fig. 8, guarantees reduce prices substantially. For B− rated offtakers price reductions of up to €40 per MWh (without considering risk-based premia) and €21 per MWh (with considering risk-based premia) are realized depending on the coverage level. Furthermore, the reductions in the case where we consider risk-based premia are about half the reductions achieved without charging premia.

The price reduction is lower when coverage is lower for most coverage levels. For example, price reductions for a coverage of 0.5 are substantially lower than price reductions for a coverage of 0.7; with and without considering risk-based premia. There is, however, an interesting exception to this. We can observe a higher price reduction from a coverage of 0.9 than from a coverage of one when considering risk-based premia as depicted in Fig. 8(b). Table 3 helps explaining this notable exception as it includes the resulting r_e for the different coverage levels. We can see that a coverage level of 0.9 already removes most of the impact from cash flow variability on r_e and that an increase in the coverage to one only leads to a slight reduction of 0.08%. In this case, the impact from the small reduction of r_e on the required PPA price is more than offset by the additional costs related to the increase of the premium.

Overall, the guarantee scheme substantially improves the cost of capital and significantly reduces the PPA price for non-investment grade rated offtakers even when risk-based premia are considered. When adhering to the principles derived in Section 2 a coverage of around 0.9 (i.e., a deductible of around 0.1) appears to be the optimal solution for this case study, because the impact of cash flow variability on r_e is almost completely removed while equity provider and lenders retain "skin in the game". Interestingly, in an already implemented, actual credit guarantee scheme the German government provides guarantees for export financing with similar levels of deductibles between 5% and 15% (Exportkreditgarantien, 2025). Hence, the implications of our case study are in line with similar already existing credit guarantee structures of the German government.

Table 3
Values of r_e for different guarantee coverage levels (Γ).

Γ	r_e
1.0	0.0700
0.9	0.0708
0.8	0.0768
0.7	0.0873
0.6	0.1013
0.5	0.1178
0.4	0.1364
0.3	0.1569
0.2	0.1791
0.1	0.2031
0.0	0.2289

Next, we compare our proposed support mechanism (i.e., PPA between private parties and a government guarantee for the offtaker default risk) with a setup where the government directly supports the project with a CfD. We choose CfDs as a reference point for support costs as CfDs are the state-of-the-art support mechanism for renewable energy assets in Europe (Zachmann, 2023). Fig. 9 shows the costs for various coverage levels compared to the base line cost of support of a CfD represented by the dashed, horizontal blue line and given by Eq. (17). We can see that even if the government carries the cost of the guarantee and does not charge risk-based premia the mechanism maybe considered advantageous from a budgetary perspective as guaranteeing PPAs are generally cheaper than directly supporting projects through CfDs.

Finally, we consider the case where a guarantee is a hard requirement for banks to lend to the project at all. As Baringa (2022) reports, lenders may not be willing to provide any debt to projects with offtakers rated below investment grade. We have investigated this effect by comparing the PPA price considering the guarantee with PPA prices without the guarantees and a debt share (δ) of zero. You may find the resulting PPA price reduction in Fig. E.12 in Appendix

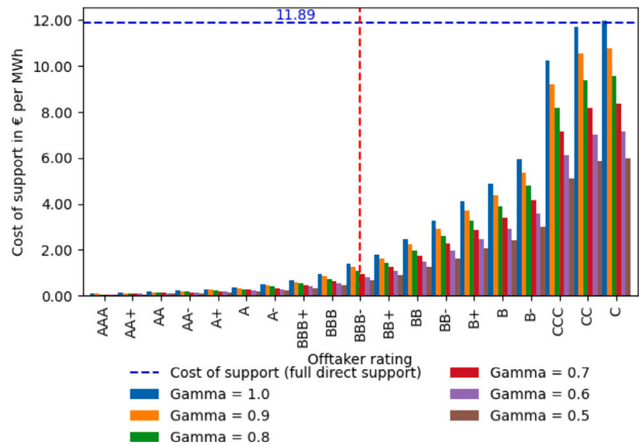


Fig. 9. Discounted expected cost of support for various guarantee coverage levels as well as for full direct support as given by Eq. (17) (horizontal dashed line). The values are also reported in Tables E.8 and E.9 in Appendix E. The vertical dashed red line indicates the last investment grade rating category.

E. Unsurprisingly, the impact of the guarantee scheme is even more pronounced in this case.

In the next section, we will summarize our results and provide policy implications as well as an outlook.

6. Conclusion

In this study, we developed a formal model that explicitly considers the cash flows of an intermittent renewable energy asset backed by a corporate PPA to establish a link between the default probability of the offtaker and the PPA price needed to meet the return requirements of the equity providers of the project. In this regard, we expanded the classical LCOE framework to incorporate offtaker-related credit risk. Offtaker defaults re-introduce market risk into the PPA backed project and hence impact revenue quality. Equity investor's returns are affected directly through expected revenue, and indirectly through the debt capacity, and hence the financing cash flow of the project. Debt capacity, in turn, depends on the revenue percentiles applied to structure the debt, which is also affected by offtaker defaults. Additionally, revenue variability matters for the returns required by the equity investors. In summary, offtaker defaults impact PPA prices via their impact on expected revenue, revenue percentiles, and revenue volatility.

We find that offtaker defaults may have a substantial impact on the PPA price, and hence the LCOE of the project depending on the survival function of the offtaker. This confirms anecdotal evidence that most corporate PPAs are backed by investment grade rated offtakers. The impact of offtaker defaults on the PPA price can be mitigated through a governmental credit guarantee scheme. We show that the five principles for the government's involvement in infrastructure projects and for providing credit guarantees (i.e., charging risk-based premia, implementing adequate monitoring, leaving a deductible, implementing asset restrictions, and requiring a collateral) may be transferred well to the context of credit guarantees for corporate PPAs. We also propose a lean credit guarantee scheme, targeting offtaker defaults, designed around allocating risk budgets to qualified lenders. In our proposed scheme, these lenders have the responsibility to carry out the credit assessment and ensure that the five principles are reflected in the project contracts and adhered to. Moral hazard and adverse selection are addressed through an ex-post evaluation of the actual defaults in the respective lenders' portfolio penalizing lenders with a reduction of their risk budget allocation or lower further allocations. Additionally, our theoretical model allows the quantification of the impact of deductibles and risk-based premia on the required PPA price.

In a case study for Germany, we quantify the effect of offtaker defaults on the PPA price. For non-investment grade rated offtakers the required PPA price ranges from 7.83 € per MWh (or 11%) up to 40.87 € per MWh (or 56%) higher than the default free price. A government guarantee scheme can mitigate the impact of defaults on the PPA price and reduce required PPA prices for B− rated offtakers up to 39.13 € per MWh (without risk-based premia) and 21.6 € per MWh (with risk-based premia) depending on the deductible of the guarantee. Therefore, even when the government charges risk-based premia, PPA prices can be reduced substantially due to de-risking the revenues and hence lowering the cost of capital of the project.

Through a guarantee scheme targeting offtaker defaults, the government may support renewable energy projects at a lower cost compared to full direct support via traditional support measures such as CfDs. Considering the auctioned volume of government support for onshore wind projects in November 2024 in Germany of 4094 MW capacity as reported by BNetzA (2024), our model estimates an expected direct support cost of €3.1 billion via CfDs. This compares to expected cost of between €465 million (for BB+ rated offtaker) and €1.6 billion (B− rated offtaker) related to a guarantee scheme. In this regard, a guarantee scheme may be the preferred option over traditional direct support schemes from a budgetary perspective. Additionally, the credit enhancement scheme crowds in the private sector with prices being the result of negotiations between private parties. Furthermore, the scheme may provide rating discovery for smaller, non-rated offtakers with the potential to eventually transition to a private market-based guarantee scheme.

A prerequisite for the guarantee scheme to work is that corporations are willing to pay a premium for directly sourced green energy and price security over long horizons in most cases. The active PPA market as reported by PEXAPARK (2024) indicates that this is the case. Our study could be extended in several ways in the future. First, we consider external default probabilities because most corporate defaults are not related to a certain PPA and electricity prices, in general. In future research, correlations between corporate defaults and electricity prices could be explored. Additionally, our model establishes a somewhat counterintuitive inverse relationship between the required PPA price and the spot market price as we assume that the project transitions to a merchant regime in case the offtaker defaults. Other assumptions concerning the implications of defaults and their influence on PPA pricing merit further investigation. Moreover, additional structural elements such as cash guarantees and the related impact on PPA prices could be evaluated. Finally, although our theoretical model is applicable to any intermittent renewable energy producer, our case study could be extended to other technologies in further research.

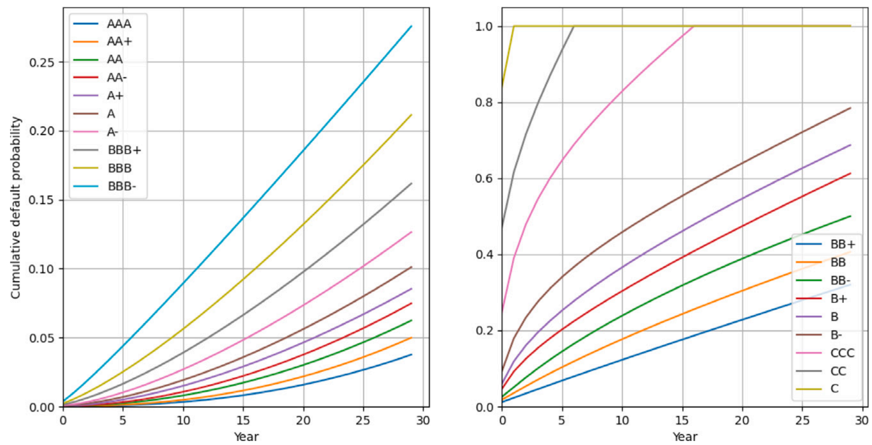


Fig. A.10. Stylized cumulative default functions from Scope Ratings GmbH (2019). The left panel depicts investment grade rating categories. The right panel depicts non-investment grade rating categories.

CRediT authorship contribution statement

Johann Schütt: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabian Kächele:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and DeepL in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Appendix A. Stylized cumulative default functions

Please note that the survival function we employ throughout the study is derived as $V(t) = 1 - F(t)$ where $F(t)$ represents the cumulative default functions displayed in Fig. A.10.

Appendix B. Details on solving the financial model for the PPA price

The following section provides the details on solving the financial model for the PPA price to reach Eq. (15). We begin with Eq. (3):

$$\sum_{t=1}^{T} \frac{E(CFE_t)}{(1-r_e)^t} = 0$$

Please note that for better readability we display Eq. (3) with a single discount rate. We will introduce risk specific discounted rates based on Eq. (5) when revenues are split into PPA backed and merchant revenues later. We may expand the cash flow to equity based on Eq. (6):

$$\sum_{t=1}^{T} \frac{-I_t - c_t(1+\Pi)^t + E(REV_t) + FCF_t}{(1+r_e)^t}$$

This can be understood as the summation of the NPVs of the various components of the cash flow to equity (capex and opex, i.e., total cost as well as revenues and the financing cash flow):

$$NPV\left(r_e, E(REV)\right) + NPV(r_e, FCF) = NPV(r_e, Cost) \tag{B.1}$$

Please note that p^{ppa} is only included in $NPV\big(E(REV)\big)$ and $NPV(FCF)$. In this regard, we continue solving for p^{ppa} isolating p^{ppa} first in $NPV\left(r_e, E(REV)\right)$ and then in $NPV(r_e, FCF)$.

Isolating the PPA price in revenues

Based on Eq. (7) net present value of the revenues is given as:

$$NPV(REV) = \sum_{t=1}^{T} \frac{V(t)\cdot p^{ppa}\cdot E(Q_t)}{(1+r_e^{ppa})^t} + \frac{\big(1-V(t)\big)\cdot E(P_t\cdot Q_t)}{(1+r_e^{m})^t}$$

Here the revenue component related to the PPA is discounted with r_e^{ppa} while the merchant revenue component is discounted with r_e^m. This way the different "riskiness" of the respective economic flows are accounted for in the model. Rearranging this equation and labeling the merchant revenue related term to $NPV\left(r_e^m, (1-V)\cdot E(Q\cdot P)\right)$ (i.e., the equity net present value of the survival function weighted merchant revenues). Further noting that the term which is multiplied with p^{ppa} represents the net present value of the weighted expected production we arrive at below expression:

$$NPV(REV) = p^{ppa}\cdot NPV\left(r_e^{ppa}, V\cdot E(Q)\right) + NPV\left(r_e^m, (1-V)\cdot E(Q\cdot P)\right) \tag{B.2}$$

Isolating the PPA price in the financing cash flow

Combining (8) with (12) yields:

$$NPV(FCF) = \sum_{t=1}^{T} \frac{debtservice_t}{(1+r_d)^t} - \sum_{t=1}^{T} \frac{debtservice_t}{(1+r_e^{ppa})^t}$$

From this rearrangement it is easily understood that debt only improves the net present value of the cash flow to equity, if the cost of debt (r_d) is lower than the required return on equity (r_e^{ppa}). Regarding the applicable discount rate for the equity investor please note that the first term determines the drawdown of the debt which reduces the outflow from an equity perspective for capex. The second term represents the (negative) value of the repayment of debt throughout the term of the loan. These flows depend on the initial structuring of the debt and hence on the distribution of the underlying $CFADS$. However, from an equity perspective these flows (i.e. interest and amortization payments) are fixed and not volatile. Hence we discount these flows with the lower equity discount rate r_e^{ppa}. As debt service per period is determined by the percentile of cash flow available for debt service Eq. (9), we may write the above expression as a function of the respective revenue percentile and the cost. Please note that for readability we indicate variables referring to the percentile used for the debt structuring with a hat:

$$\sum_{t=1}^{T} \frac{\hat{REV}_t - (1+\Pi)^t\cdot c_t}{(1+r_d)^t} - \sum_{t=1}^{T} \frac{\hat{REV}_t - (1+\Pi)^t\cdot c_t}{(1+r_e^{ppa})^t} \tag{B.3}$$

$$p^{ppa} = \frac{NPV(r_d, Cost) - NPV\left(r_e^m, (1-V)\cdot E(P\cdot Q)\right) - NPV\left(r_d, (1-V)\cdot \widehat{P\cdot Q}\right) + NPV\left(r_e^{ppa}, (1-V)\cdot \widehat{P\cdot Q}\right)}{NPV\left(r_e^{ppa}, V\cdot E(Q)\right) + NPV(r_d, V\cdot \hat{Q}) - NPV(r_e^{ppa}, V\cdot \hat{Q})} \tag{B.5}$$

Box II.

Again, we note that p^{ppa} is only included in revenues. Hence, we continue isolating p^{ppa} in $R\hat{E}V_t$ similarly to (B.2):

$$\sum_{t=1}^{T} R\hat{E}V_t = p^{ppa}\cdot\sum_{t=1}^{T}(V(t)\cdot\hat{Q}_t) + \sum_{t=1}^{T}((1-V(t))\cdot\widehat{P_t\cdot Q_t})$$

With $\hat{Q}_t$ and $P_t\hat{Q}_t$ representing the structuring percentile of the production and the merchant revenues, respectively. Isolating p^{ppa} the NPV of the financing cash flow may be written as a collection of NPVs:

$$\begin{aligned} NPV(r_e, FCF) = p^{ppa}\cdot &\left(NPV(r_d, V\cdot\hat{Q}) - NPV(r_e^{ppa}, V\cdot\hat{Q})\right)\\ &+ NPV(r_d,(1-V)\cdot\widehat{P\cdot Q})\\ &- NPV(r_e^{ppa},(1-V)\cdot\widehat{P\cdot Q})\\ &- NPV(r_d, Cost) + NPV(r_e^{ppa}, Cost)\end{aligned} \tag{B.4}$$

Solution for the PPA price

Plugging (B.2) and (B.4) into (B.1) and solving for p^{ppa} gives Eq. (15) (see the equation in Box II). Setting $V(t)=1$ for every period gives the non-default case which yields the same result as the standard LCOE approach as shown in Eq. (1):

$$p^{ppa} = \frac{NPV(r_d, Cost)}{NPV(r_e, E(Q)) + NPV(r_d,\hat{Q}) - NPV(r_e,\hat{Q})} \tag{B.6}$$

Appendix C. Calibration of the required return on equity (r_e) and the risk tolerance coefficient (τ)

As stated in the text, we assume that the equity provider has a mean–variance utility and that the utility is driven by returns and the variability of total revenues over the life time of the project ($TREV = \sum_{t=0}^{t=T} REV_t$). We measure variability with the coefficient of variation:

$$CV = \frac{\sigma}{\mu} \tag{C.1}$$

The required return on equity is than given by:

$$r_e \geq \frac{CV(TREV)}{\tau}. \tag{C.2}$$

τ represents the risk-tolerance coefficient. For our case study we calibrate τ with the following procedure:

1. Assume that the r_e of 7.0% provided by Fraunhofer ISE (2024) represents the return requirements for projects without default risk, i.e., backed by a CfD or a FiT.
2. Simulate 10.000 paths of $TREV$ under the assumption that there are no defaults and that the project earns the default free price p^{ppa}_{lcoe}.
3. Calculate the CV of the $TREV$ based on the generated paths.
4. Plug the 7.0% and derived CV into Eq. (C.2) and solve for τ.

τ is than applied to derive the required return for the merchant cases.

Appendix D. Historical correlations of prices and wind capacity factors

Fig. D.11 depicts the historical rolling correlation as well as the correlation in the simulated data. Note that both fluctuate within the same range; thus, the correlation in our simulated data seems to be a good fit.

Table E.4
PPA prices in € per MWh for different guarantee coverage levels without considering risk-based premia.

	No guarantee ($\Gamma = 0$)	$\Gamma = 0.1$	$\Gamma = 0.2$	$\Gamma = 0.3$	$\Gamma = 0.4$
AAA	73.01	72.99	72.97	72.95	72.91
AA+	73.14	73.12	73.09	73.05	73.01
AA	73.35	73.32	73.27	73.22	73.16
AA−	73.54	73.49	73.44	73.37	73.29
A+	73.79	73.73	73.66	73.57	73.47
A	74.06	73.99	73.90	73.79	73.66
A−	74.55	74.45	74.33	74.18	74.00
BBB+	75.30	75.16	74.99	74.80	74.56
BBB	76.39	76.20	76.01	75.76	75.41
BBB−	78.41	78.19	77.89	77.49	76.95
BB+	80.51	80.20	79.78	79.22	78.48
BB	84.28	83.81	83.16	82.32	81.23
BB−	89.06	88.36	87.44	86.24	84.71
B+	95.30	94.30	92.99	91.31	89.18
B	101.70	100.37	98.67	96.50	93.76
B−	113.55	111.60	109.13	106.03	102.15
CCC	224.13	216.46	207.00	195.37	181.06
CC	523.73	499.49	470.24	434.77	392.00
C	4511.60	4268.52	3978.96	3629.10	3205.23

Table E.5
PPA prices in € per MWh for different guarantee coverage levels without considering risk-based premia.

	$\Gamma = 0.5$	$\Gamma = 0.6$	$\Gamma = 0.7$	$\Gamma = 0.8$	$\Gamma = 0.9$	$\Gamma = 1.0$
AAA	72.88	72.83	72.78	72.73	72.69	72.68
AA+	72.96	72.89	72.82	72.75	72.70	72.68
AA	73.08	72.99	72.89	72.79	72.71	72.68
AA−	73.19	73.08	72.94	72.81	72.72	72.68
A+	73.34	73.19	73.02	72.85	72.73	72.68
A	73.50	73.31	73.10	72.90	72.74	72.68
A−	73.79	73.53	73.25	72.97	72.76	72.68
BBB+	74.24	73.87	73.48	73.09	72.79	72.68
BBB	74.97	74.41	73.80	73.26	72.84	72.68
BBB−	76.26	75.41	74.44	73.56	72.93	72.68
BB+	77.55	76.40	75.10	73.86	73.02	72.68
BB	79.86	78.19	76.30	74.41	73.18	72.68
BB−	82.78	80.45	77.81	75.17	73.38	72.68
B+	86.53	83.34	79.75	76.16	73.64	72.68
B	90.37	86.31	81.73	77.17	73.91	72.68
B−	97.39	91.72	85.36	79.02	74.41	72.68
CCC	163.69	143.18	120.10	96.84	79.24	72.68
CC	340.65	279.97	211.99	143.94	92.25	72.68
C	2695.21	2097.23	1430.93	766.89	263.13	72.68

Appendix E. Simulation results for PPA prices and support cost

See Fig. E.12 and Tables E.4–E.9.

Data availability

https://github.com/JohannHCS/offtaker_defaults_ppa.

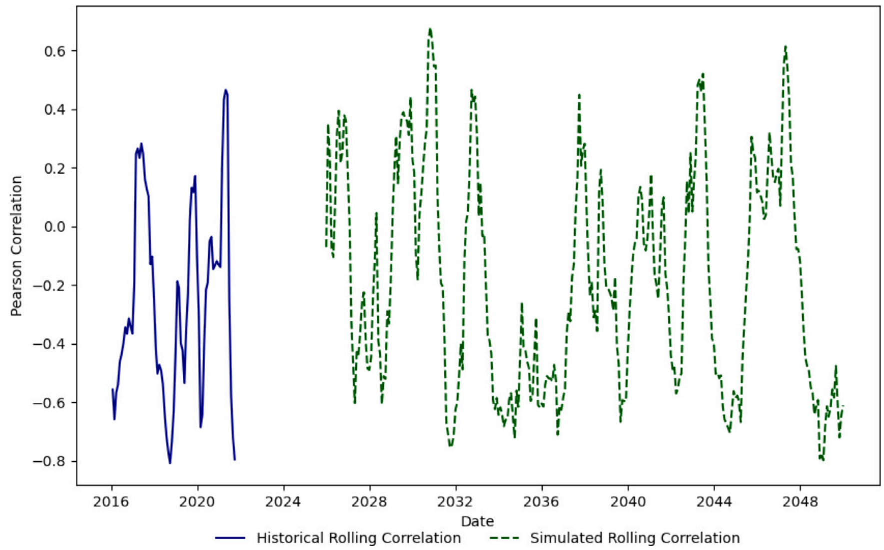
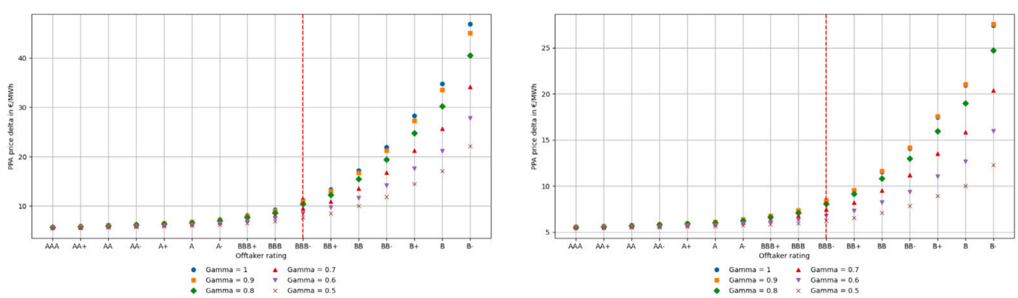


Fig. D.11. Historical and simulated rolling correlations of wind capacity factors and market values.



(a) Without considering risk-based premia

(b) Considering risk-based premia

Fig. E.12. Reduction of required PPA prices for various guarantee coverage levels considering that no debt ($\delta = 0$) is provided without the guarantee. The left panel depicts values without considering risk-based premia, and the right panel includes them.

Table E.6
PPA prices in € per MWh for different guarantee coverage levels with considering risk-based premia.

	No guarantee ($\Gamma = 0$)	$\Gamma = 0.1$	$\Gamma = 0.2$	$\Gamma = 0.3$	$\Gamma = 0.4$
AAA	73.01	73.01	73.00	73.00	72.98
AA+	73.14	73.14	73.14	73.13	73.11
AA	73.35	73.35	73.34	73.33	73.30
AA−	73.54	73.54	73.53	73.51	73.47
A+	73.79	73.79	73.77	73.75	73.70
A	74.06	74.06	74.04	74.00	73.94
A−	74.55	74.54	74.52	74.47	74.39
BBB+	75.30	75.29	75.25	75.21	75.10
BBB	76.39	76.39	76.40	76.33	76.18
BBB−	78.41	78.49	78.48	78.37	78.12
BB+	80.51	80.60	80.57	80.40	80.05
BB	84.28	84.38	84.31	84.05	83.53
BB−	89.06	89.17	89.05	88.66	87.92
B+	95.30	95.40	95.19	94.61	93.58
B	101.70	101.78	101.48	100.72	99.38
B−	113.55	113.57	113.07	111.94	110.02
CCC	224.13	223.80	221.68	217.36	210.37
CC	523.73	521.02	513.29	499.31	478.08
C	4511.60	4476.30	4394.53	4253.29	4038.61

Table E.7
PPA prices in € per MWh for different guarantee coverage levels with considering risk-based premia.

	$\Gamma = 0.5$	$\Gamma = 0.6$	$\Gamma = 0.7$	$\Gamma = 0.8$	$\Gamma = 0.9$	$\Gamma = 1.0$
AAA	72.96	72.94	72.90	72.87	72.85	72.85
AA+	73.08	73.04	72.99	72.95	72.92	72.92
AA	73.26	73.20	73.13	73.07	73.02	73.03
AA−	73.42	73.34	73.26	73.17	73.12	73.12
A+	73.63	73.53	73.42	73.31	73.24	73.25
A	73.86	73.74	73.60	73.46	73.38	73.39
A−	74.27	74.11	73.92	73.74	73.62	73.63
BBB+	74.93	74.67	74.41	74.15	73.99	74.01
BBB	75.93	75.56	75.12	74.76	74.53	74.56
BBB−	77.73	77.17	76.50	75.85	75.51	75.54
BB+	79.51	78.76	77.86	76.95	76.48	76.52
BB	82.73	81.64	80.32	79.01	78.24	78.30
BB−	86.80	85.27	83.44	81.62	80.47	80.55
B+	92.03	89.95	87.46	84.98	83.37	83.47
B	97.40	94.75	91.58	88.44	86.39	86.50
B−	107.23	103.53	99.13	94.78	91.95	92.09
CCC	200.32	187.15	171.53	155.86	145.48	145.98
CC	448.40	409.61	363.72	318.01	287.94	289.19
C	3739.11	3353.00	2900.63	2453.03	2159.96	2170.25

Table E.8
Cost of support in € per MWh for various guarantee coverage levels.

	$\Gamma = 0.1$	$\Gamma = 0.2$	$\Gamma = 0.3$	$\Gamma = 0.4$	$\Gamma = 0.5$
AAA	0.01	0.02	0.03	0.04	0.05
AA+	0.01	0.03	0.04	0.05	0.06
AA	0.02	0.04	0.05	0.07	0.09
AA−	0.02	0.05	0.07	0.09	0.11
A+	0.03	0.06	0.09	0.12	0.15
A	0.04	0.07	0.11	0.15	0.18
A−	0.05	0.10	0.15	0.19	0.24
BBB+	0.07	0.13	0.20	0.27	0.34
BBB	0.09	0.19	0.28	0.37	0.47
BBB−	0.14	0.28	0.41	0.55	0.69
BB+	0.18	0.36	0.54	0.72	0.89
BB	0.25	0.50	0.74	0.99	1.24
BB−	0.33	0.65	0.98	1.30	1.63
B+	0.41	0.82	1.23	1.65	2.06
B	0.49	0.97	1.46	1.95	2.43
B−	0.60	1.19	1.79	2.39	2.98
CCC	1.02	2.04	3.07	4.09	5.11
CC	1.17	2.34	3.51	4.68	5.86
C	1.20	2.39	3.59	4.78	5.98

Table E.9
Cost of support in € per MWh for various guarantee coverage levels.

	$\Gamma = 0.6$	$\Gamma = 0.7$	$\Gamma = 0.8$	$\Gamma = 0.9$	$\Gamma = 1.0$
AAA	0.05	0.06	0.07	0.08	0.09
AA+	0.08	0.09	0.10	0.11	0.13
AA	0.11	0.13	0.15	0.16	0.18
AA−	0.14	0.16	0.18	0.21	0.23
A+	0.18	0.21	0.24	0.27	0.29
A	0.22	0.25	0.29	0.33	0.36
A−	0.29	0.34	0.39	0.44	0.49
BBB+	0.40	0.47	0.54	0.60	0.67
BBB	0.56	0.65	0.74	0.84	0.93
BBB−	0.83	0.96	1.10	1.24	1.38
BB+	1.07	1.25	1.43	1.61	1.79
BB	1.49	1.74	1.98	2.23	2.48
BB−	1.96	2.28	2.61	2.93	3.26
B+	2.47	2.88	3.29	3.70	4.11
B	2.92	3.41	3.90	4.38	4.87
B−	3.58	4.18	4.77	5.37	5.97
CCC	6.13	7.16	8.18	9.20	10.22
CC	7.03	8.20	9.37	10.54	11.71
C	7.18	8.37	9.57	10.76	11.96

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