

Feed-in Tariff Contract Schemes and Regulatory Uncertainty

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Abstract

This paper presents a novel analysis of two feed-in tariffs (FIT) under market and regulatory uncertainty, namely a sliding premium with cap and floor and a minimum price guarantee. Regulatory uncertainty is modeled with a Poisson process, whereby a jump event may reduce the tariff before the signature of the contract. Using a semi-analytical real options framework, we derive the project value, the optimal investment threshold, and the value of the investment opportunity for these schemes. Taking into consideration the optimal investment threshold, we also compare the two aforementioned FITs with the fixed-price FIT and the fixed-premium FIT, which are policy schemes that have been extensively studied in the literature. Our results show that increasing the likelihood of a jump event lowers the investment threshold for all the schemes; moreover, the investment threshold also decreases when the tariff reduction increases. We also compare the four schemes in terms of the corresponding optimal investment thresholds. For example, we find that the investment threshold of the sliding premium is lower than the minimum price guarantee. This result suggests that the first regime is a better policy than the latter because it accelerates the investment while avoiding excessive earnings for producers or excessive payments for consumers.

Keywords: Investment analysis, Real Options, Feed-in Tariff, Regulatory Uncertainty

JEL Classification: L94, Q42, C72

1 Introduction

The quest for an optimal policy for incentivizing renewable energy production has led policy-makers to create several support schemes over the past decades. Many jurisdictions use different instruments to support renewable energy production, such as feed-in tariffs, quota obligations with green-certificate trading, tenders, and tax exemptions. A key aim of these support schemes is to accelerate the investment decision of renewable energy projects while making energy production more sustainable (Couture & Gagnon 2010).

According to the Renewables 2019 Global Status Report (REN21 2019), 111 jurisdictions were using feed-in tariff policies by the end of 2018, while 48 jurisdictions held auctions (i.e., tenders) in 2018, and 33 jurisdictions were using quota obligations with green-certificate trading in 2018. We can thus conclude that feed-in policies continue to play an important role in the policy-making landscape of renewable energies.

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Feed-in tariffs (FITs) are price-based schemes with long-term contracts, whereby an investor receives a fixed or variable remuneration for a long period (e.g., 15 - 20 years). According to Couture & Gagnon (2010), the feed-in policies can thus be classified into two groups. First, the market-independent FITs are long-term contracts that pay remunerations that are not tied to the energy market price. These feed-in policies are suited to support small scale projects or less-mature technologies because they protect investors from price risk and thus reduce the cost of capital. The second group is the market-dependent FITs or feed-in premiums, whereby investors receive a fixed or variable premium over the energy market price. This category includes support schemes such as a fixed premium, a minimum price guarantee, and a sliding premium with cap and floor¹.

The European Commission (2013) sent out a recommendation for policymakers to shift from the popular market-independent FITs to the feed-in premiums, because they believe that energy market signals should be the key drivers of investment and production decisions. Feed-in premiums can thus create incentives for producers to optimize investment decisions, plant design, and production according to market signals.

This work uses the real options framework to present a novel analysis of two feed-in premiums, namely a FIT with a minimum price guarantee (i.e., price-floor regime) and a FIT with a sliding premium with cap and floor (henceforth called sliding premium). We also compare these two feed-in premiums with two popular feed-in tariffs, namely a fixed price and a fixed premium, that serve as baselines for our analysis. The aim is to compare the key aspects of these support schemes that trigger a renewable energy investment not only from an investor's perspective but also from a policymaker's viewpoint. Netherlands (Agnolucci 2007), Ireland (Doherty & O'Malley 2011), and Switzerland (Couture, Kreyck & Williams 2010) are examples of jurisdictions that have used variations of the price-floor regime within a FIT contract. In addition, Spain (Barcelona 2012) is an example of a jurisdiction that used the sliding-premium regime.

Since its inception in 1978, policy revisions of FITs have occurred due to changing market conditions and the need to meet specific goals of each jurisdiction. Ritzenhofen & Spinler (2016) state that policymakers adjust feed-in policies in order to accelerate renewable energy investments and to find cost-effective policies that are subject to budget constraints. Hence, we also analyze the impact of policy revisions on the optimal investment timing of feed-in premiums.

This work aims to shed some light on some challenging policy-making decisions. In particular, we focus on the following research questions:

- How does a FIT with a minimum price guarantee and a FIT with a sliding premium affect the timing of an investment decision, especially in comparison with other feed-in policies that have been extensively studied in the literature?
- How does regulatory uncertainty impact the timing of an investment decision when policymakers may reduce the tariff of these two feed-in premiums?

Within the scientific literature, Kim & Lee (2012) also compare four different feed-in policies, namely the fixed price, the fixed premium, the minimum price guarantee, and the sliding premium. However, the work focuses on a different optimization problem, where the authors optimize the tariffs in order to maximize the number of sign-ups. In contrast, our work tackles a different optimization problem, where we consider a fixed tariff and derive the optimal investment thresholds. In the same line of research, the paper from Chronopoulos, Hagspiel & Fleten (2016) focuses on the same problem as our work, where policy uncertainty is also taken into consideration. However, the work only analyzes a fixed-premium FIT and not the minimum price guarantee and the sliding premium. We thus build on these previous research works to present a more complete analysis of FITs and how the optimal investment timing can change under regulatory uncertainty.

¹The feed-in premium payments can be designed to be either a fixed predetermined amount over the market price or a sliding premium where the premium varies as a function of the market price.

Comparing our results with the work from Chronopoulos, Hagspiel & Fleten (2016), we also find that investment accelerates when the fixed-premium FIT has a higher probability of retraction. In addition, we show that this results holds for the other feed-in policies, because investors anticipate the decision in order to obtain a higher tariff. Our results also show that the risk of a tariff reduction has a higher impact on the optimal investment timing of the fixed-price and the fixed-premium regimes than the minimum price guarantee and the sliding-premium regimes. We also present more results aimed at policy-making decisions, when comparing the optimal investment thresholds of the FIT schemes. For instance, the investment threshold of the sliding premium is lower than the threshold of the minimum price guarantee. This result suggests that the sliding premium is a better policy than the minimum price guarantee because the former policy scheme accelerates the investment while avoiding excessive earnings² for producers or excessive payments for consumers.

The remainder of this paper is organized as follows. Section 2 presents the literature review and our main contributions to literature. In Section 3, we formalize the optimization problem that this paper addresses, and we present results concerning the value of investment. Section 4 presents the investment decision (the value of the project and the investment thresholds) for the four different FIT policies, namely the sliding premium, the minimum price guarantee, the fixed price, and fixed premium. Section 5 presents the analytical and numerical study of the investment thresholds for all types of FIT design. Finally, we present the concluding remarks in Section 6.

2 Literature review

Myers (1977) was the first scholar to coin the term “real options” with an aim to create a methodology to better value investment projects in the presence of managerial flexibilities. Tourinho (1979) presented the first real options framework which analyzed the option to extract oil when future prices are uncertain. A few years later, Brennan & Schwartz (1985) used the real options framework to analyze mineral extraction investments. In addition, McDonald & Siegel (1986) derived the optimal investment rule which takes into account the value of waiting. The authors show that the standard net present value (NPV) analysis is grossly wrong.

Many managers in the corporate world rely on the NPV rule to analyze investment projects. A project with a positive NPV is considered to have a profitable outcome. In contrast, a negative NPV is considered to result in a net loss. However, the standard NPV valuation does not take into account uncertainties and managerial flexibilities that are present in dynamic environments; thus, it underestimates the value of the project. For example, the NPV method does not add the value of several “options” (i.e., managerial flexibilities) that managers use in practice, such as gathering information from the market and waiting to invest until market conditions are favorable. Consequently, a project with a positive NPV may be optimally deferred, or a project with a negative NPV may lead to a profitable outcome due to the added value of these options. For instance, the case study from Rocha, Barbosa, Garcia, Sardinha & Teixeira (2007) shows how the added value of these options can impact an investment project. The real options approach can thus provide a good framework to value investment in the presence of uncertainties and managerial flexibilities, such as renewable energy projects.

According to Ceseña, Mutale & Rivas-Dávalos (2013), the real options approach can be very useful for the decision-making process of renewable energy investments. Renewable energy projects are irreversible and present several uncertainties, such as market price uncertainty and regulatory uncertainty. In addition, managers have several options in the decision-making process, such as the waiting option.

In fact, many scholars have used the real options approach to analyze renewable energy tech-

²Many works that have analyzed a FIT with a sliding premium state that this policy scheme avoids excessive earnings for producers, such as the work from Cossent, Gómez & Olmos (2011).

nologies in the scientific literature. For instance, Shao, Yang & Zhang (2017) proposed a framework for policymakers that finds the optimal subsidies or optimal price discount rates to incentivize the adoption of electric vehicles. Bonneuil & Boucekine (2016) analyze the optimal moment for adopting renewable energies and the optimal rate of adoption. Kowalski, Stagl, Madlener & Omann (2009) use a participatory multi-criteria analysis to assess different renewable energy scenarios of technology deployment. However, these works do not analyze the feed-in tariffs as an incentive to accelerate the investment decision of renewable energy projects.

Doherty & O'Malley (2011) use a real options approach to analyze the Irish REFIT program, which is a variation of a FIT with a minimum price guarantee. With a Generalized Extreme Value distribution, the authors forecast the mean expected market value of wind and the value of the put option, given a strike price, in order to analyze the efficiency of the Irish FIT scheme in comparison with the fixed-price FIT. The results show that the Irish FIT scheme creates a similar or lower incentive than the fixed-price FIT for wind projects. Kim & Lee (2012) present an analysis of four different FIT schemes, namely fixed price, fixed premium, minimum price guarantee, and sliding premium. In particular, the work uses a binomial lattice and simulation (i.e., real options numerical technique) to compare the four different FITs, whereby the work focuses on how different scenarios (e.g., markets with different price volatilities) can impact the number of sign-ups of renewable energy projects. The results suggest that the number of sign-ups increases in more volatile markets, to the detriment of a higher cost for ratepayers. While these two research works analyze FIT schemes from an efficiency viewpoint, they are based on a different optimization problem. In particular, these works do not analyze the optimal investment thresholds and the influence of regulatory uncertainty on the timing of the investment decision.

Boomsma, Meade & Fleten (2012) examine renewable energy investments under different policy schemes, namely a fixed-price FIT, a fixed-premium FIT, and a renewable energy certificate trading scheme. With a semi-analytical framework, the authors derive the optimal investment threshold and the optimal capacity to install. The work also assumes multiple sources of uncertainty (e.g., steel spot price and subsidy payment) and uncertainty with respect to any change of support scheme. The results show that fixed-price FITs create incentives for speeding up investment while the certificate trading generates larger projects. Following a similar approach, Boomsma & Linnerud (2015) employ a semi-analytical real options framework to analyze policy uncertainty for the same policy schemes in Boomsma, Meade & Fleten (2012). The policy uncertainty considers that a scheme may be terminated at any point in time. The results show that policy uncertainty increases the investment threshold when the termination decision is retroactively applied. In contrast, investment is accelerated when the decision is not retroactively applied. Our work is significantly different from Boomsma, Meade & Fleten (2012) and Boomsma & Linnerud (2015) because we derive two new support schemes, namely the minimum price guarantee and sliding premium. In addition, our numerical study has novel results for policymakers regarding the comparison of the optimal investment thresholds of four FIT schemes.

Ritzenhofen & Spinler (2016) use a real options approach to analyze the effect of regulatory uncertainty on investment behavior, where a policymaker may decide to switch from a fixed-price FIT to a free-market regime (or the reverse case). The research work shows that regulatory uncertainty delays the investment when the FIT tariff is close to the market price. If the FIT tariff is significantly higher than the market price, then the regulatory uncertainty accelerates investment behavior. With a semi-analytical real options framework, Chronopoulos, Hagspiel & Fleten (2016) also analyze the same optimization problem as our work. The model includes a fixed-premium FIT where investment may occur within a single stage or through multiple stages. The work uses a Poisson process to model the policy uncertainty, whereby the FIT may be introduced or retracted multiple times. The results show that investment accelerates when the fixed-premium FIT has a higher probability of retraction, which is the same result in our work. However, we show that this result also holds for the other FIT schemes. In addition, the authors find that a permanent subsidy retraction reduces the amount of capacity installed.

In summary, these two research works analyze a renewable energy investment under regulatory uncertainty; however, our work has several differences. First, we analyze two new FITs, namely a minimum price guarantee and a sliding premium, which are not included in the analysis of these two papers. Second, we consider that a policymaker may reduce the tariff instead of a regime-switching scenario of subsidies. Lastly, we present several policy-related results regarding the optimal investment thresholds of the aforementioned feed-in premiums that are not discussed in these two papers.

Our work builds on the research work from Adkins, Paxson, Pereira & Rodrigues (2019), in which the authors present a semi-analytical real options model for finite-lived collars. In particular, the work compares the key differences between perpetual collars and finite-lived or retractable collars. The results show that the retractable and finite-lived collars can significantly impact the optimal investment threshold when compared to the perpetual collars. However, our work is distinct from the aforementioned work because we tailor the finite-lived collar model for a sliding-premium FIT under regulatory uncertainty. We also compare the sliding premium under regulatory uncertainty with other feed-in policies that have been studied in the scientific literature.

In summary, to the best of our knowledge, our paper presents a novel analysis of the optimal investment thresholds of finite-lived FITs with a minimum price guarantee and a sliding premium under regulatory uncertainty, whereby a policymaker may reduce the tariff before the signature of the contract. With a semi-analytical real options framework, we derive the value of the project, the option value, and the optimal investment threshold of each FIT scheme. In addition, we also compare these two FITs with a fixed-price FIT and a fixed-premium FIT in order to draw conclusions for both investors and policymakers.

3 The value of investment

Throughout the paper, we assume that the energy market price changes stochastically over time, under the risk-neutral measure. We denote it by $P = \{P_t, t \geq 0\}$, where P is the solution of the following stochastic differential equation:

$$dP_t = \mu P_t dt + \sigma P_t dB_t \quad (1)$$

with $B = \{B_t, t \geq 0\}$ being a Brownian motion, μ the risk-neutral drift, and σ the volatility.

Note that we assume that energy market prices follow a geometric Brownian motion and this can be considered a simplifying assumption. However, if we consider other dynamics - like a mean-reverting process - the change in the qualitative results would be small, according to Schwartz (1998). Moreover, as suggested by Boomsma, Meade & Fleten (2012), the drift μ can be estimated from forward/futures prices.

We assume that before investment the firm has a zero payoff and that the investment cost is I . We let r denote the interest rate under the risk-neutral measure. In order to avoid trivial or ill-posed problems, we assume that $\mu < r$. The optimization problem that we want to address is the following:

$$W_S(P) = \sup_{\tau} E \left[\int_{\tau}^{\infty} \pi_S(P_t) e^{-rt} dt - I e^{-r\tau} | P_0 = P \right] \quad (2)$$

where π_S denotes the profit function upon investment, that we assume to be of the following type:

$$\pi_S(P_t) = \begin{cases} \Pi_S(P_t) & \tau \leq t \leq \tau + T \\ P_t Q & t > \tau + T \end{cases} \quad (3)$$

with τ being the time at which investment takes place, Π_S is the profit of the firm as long as the subsidy is received, and T is the duration of the contract.

Throughout this paper, we consider four types of subsidy schemes, which lead to different investment strategies of the firm. Therefore, we use the subscript S to denote the particular subsidy that we are considering. The subsidies impact the profit function Π_S of the firm as we will see. Furthermore, we assume that after the subsidy has been removed, the profit of the firm depends solely on the market price and the quantity Q (total annual production), which we assume to be fixed over time. We note that similar assumptions have been used in Boomsma, Meade & Fleten (2012) and Boomsma & Linnerud (2015), for instance.³

If the firm invests at time τ when the current energy market price is P , then it will receive the following amount:

$$V_S(P) = E \left[\int_{\tau}^{\tau+T} \Pi_S(P_t) e^{-rt} dt + \int_{\tau+T}^{\infty} P_t Q e^{-rt} dt \mid P_0 = P \right]. \quad (4)$$

Using (4) in (2), we conclude that the optimization problem that we propose to solve is the following:

$$W_S(P) = \sup_{\tau} E \left[\int_{\tau}^{\tau+T} \Pi_S(P_t) e^{-rt} dt + \int_{\tau+T}^{\infty} P_t Q e^{-rt} dt - I e^{-r\tau} \mid P_0 = P \right]. \quad (5)$$

The problem described in (5) is a standard investment problem, which can be solved using the dynamic programming principle. We refer, for instance, to Dixit & Pindyck (1994), for the main results about investment problems in a context of real options. Applying such results leads to the following (general) solution of (5):

$$W_S(P) = \begin{cases} A_1 P^{\beta_1} & 0 < P < P^* \\ V_S(P) - I & P \geq P^* \end{cases} \quad (6)$$

with

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2} \right)^2 + \frac{2r}{\sigma^2} \right)^{\frac{1}{2}} > 1 \quad (7)$$

and A_1 and P^* being such that $A_1 P^{*\beta_1} = V_S(P^*) - I$ and $\beta_1 A_1 P^{*\beta_1-1} = V'_S(P^*)$ (i.e., the so-called value matching and smooth pasting conditions).

In the remainder of the paper, we let F denote the feed-in tariff and assume it to be fixed. The four different types of feed-in tariff contracts that we consider in this paper are the following:

- Sliding premium, with $\Pi_C(P) := \min(\max(P, F), C) Q$; in this particular case, the tariff F corresponds to the price floor, C is the price cap, and $C \geq F$.
- Minimum price guarantee, with $\Pi_M(P) := \max(P, F) Q$.
- Fixed-price scheme, for which $\Pi_F(P) := F Q$.
- Fixed-premium scheme, for which $\Pi_P(P) := (P + F) Q$.

Moreover, in this paper, we extend the framework to include policy uncertainty, whereby a downward jump in the tariff F may occur according to a Poisson process. Note that the Poisson process was also used in Boomsma & Linnerud (2015) and Chronopoulos, Hagspiel & Fleten (2016) to model policy uncertainty⁴.

³In their papers, the authors assume that the production is fixed, depending only on the capacity installed by the firm. Although for short intervals of time, production of renewable energy sources vary with weather conditions, for longer intervals the production is more stable.

⁴Alternative approaches, such as regime switching, have been used by Boomsma, Meade & Fleten (2012) and Ritzenhofen & Spinler (2016).

Let Y denote the time at which this change in the tariff occurs; in view of the assumption of a Poisson process, Y is a random variable, that follows an exponential distribution with parameter λ . We assume, furthermore, that the price process in (1) and the time at which this tariff change occurs are uncorrelated. Moreover, the tariff decreases by multiplying the tariff F with ω (i.e., the new tariff is equal to ωF), where $0 \leq \omega \leq 1$.

In order to take into account the reduction of the tariff, we change slightly the notation, where $\Pi_S(P, F)$ and $\pi_S(P, F)$, for $S \in \{M, F, P\}$ ⁵, denote the profit flow under regime S when the tariff received is equal to F . In addition, $\Pi_S(P, \omega F)$ denotes the corresponding the profit flow after a change that reduces the subsidy, i.e., changing from F to ωF . In case of retraction of a subsidy (i.e., the subsidy is totally abolished), $\Pi_S(P, 0)$ denotes the profit flow after a change.

For the sliding premium case, we also use a similar notation as above. Since this subsidy has a cap (C) and a floor (F), we denote the profit flow by $\Pi_C(P, F, C)$. Thus, $\Pi_C(P, \omega F, \omega_C C)$ is the profit flow when the price floor is reduced to ωF and the price cap to $\omega_C C$.

We assume that once the firm invests, there will not be any change in the FIT contract (i.e., the tariff F does not change after the firm invests). Therefore, the optimization problem may be written as follows:

$$W_{SR}(P) = \sup_{\tau} E \left[\int_{\tau}^{\tau+T} e^{-rt} (\Pi_S(P_t, \omega F) 1_{\{Y < \tau\}} + \Pi_S(P_t, F) 1_{\{Y > \tau\}}) dt + \frac{PQ}{r - \mu} e^{-(r-\mu)(\tau+T)} \right] \quad (8)$$

with $1_{\{Y < \tau\}} = 1$ if $Y < \tau$ and $1_{\{Y > \tau\}} = 1$ if $Y > \tau$. We use the notation W_{SR} in order to distinguish the case of **R**egulatory uncertainty. Therefore, once the firm decides to undertake the investment, we assume that there is no uncertainty about the tariff contract.

With these remarks, we proceed with the analysis of the problem. We need to consider two cases:

- i) The tariff has already decreased, thus the firm knows that the tariff is ωF during a period T . Therefore, we denote $W_S^{(\omega)}(P)$ as a value function equal to W_S , as defined in (6), where we substitute ωF for F .
- ii) At the current time, the value of the tariff has not been subject to a decrease. In this case, there is uncertainty about the evolution of the prices and the time at which the reduction of the subsidy will occur (relevant only before the investment time). Let P_{SR}^* denote the investment threshold when the subsidy is still active but there is uncertainty about the time it will be changed. For prices P smaller than this value P_{SR}^* , the investment is not yet optimal. Therefore the value function in this region is solution of the following differential equation:

$$\mu P \frac{\partial W_{SR}(P)}{\partial P} + 0.5\sigma^2 P^2 \frac{\partial^2 W_{SR}(P)}{\partial P^2} - rW_{SR}(P) + \lambda[W_S^{(\omega)}(P) - W_{SR}(P)] = 0 \quad (9)$$

where $1/\lambda$ denotes the expected time until the change in the policy occurs. In (10), the term $[W_S^{(\omega)}(P) - W_{SR}(P)]$ accounts for the change in the value in case the tariff decreases, which, in an infinitesimal interval, occurs with probability λdt . Note that this term is precisely the major difference with the case where there is not regulatory uncertainty. See Øksendal & Sulem (2005) for further details.

Recall that $W_S^{(\omega)}(P)$ is (6) substituting ωF for F . If we let $P^{*(\omega)}$ denote the corresponding investment threshold when the tariff is ωF , then, as $\omega < 1$, the investment trigger with ωF is greater than the investment trigger with F , because if one does not invest when the tariff is F , he will not invest when the tariff is $\omega F < F$ either. Therefore, the second branch in

⁵ M, F, P corresponds to minimum price guarantee, fixed price, and fixed premium, respectively.

(6) will never occur, and thus $W_S^{(\omega)}(P)$ is then equal to $A_1^{(\omega)}P^{\beta_1}$. It follows then that the value function before the investment must be the solution of the following equation:

$$\mu P \frac{\partial W_{SR}(P)}{\partial P} + 0.5\sigma^2 P^2 \frac{\partial^2 W_{SR}(P)}{\partial P^2} - rW_{SR}(P) + \lambda[A_1^{(\omega)}P^{\beta_1} - W_{SR}(P)] = 0 \quad (10)$$

In general, the solution of (10) is of the following form (Nunes & Pimentel 2017):

$$W_{SR}(P) = B_1P^{\eta_1} + A_1^{(\omega)}P^{\beta_1} \quad (11)$$

where η_1 is the positive root of the quadratic equation:

$$0.5\sigma^2\eta(\eta - 1) + \mu\eta - (r + \lambda) = 0. \quad (12)$$

Hence,

$$\eta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2} \right)^2 + \frac{2(r + \lambda)}{\sigma^2} \right)^{\frac{1}{2}}. \quad (13)$$

Therefore, in case of regulatory uncertainty, the value function takes the following form:

$$W_{SR}(P) = \begin{cases} B_1P^{\eta_1} + A_1^{(\omega)}P_{SR}^{\beta_1} & 0 < P < P_{SR}^* \\ V_S(P) - I & P \geq P_{SR}^* \end{cases} \quad (14)$$

where, as previously defined, P_{SR}^* denotes the investment threshold when the feed-in tariff used is S and under regulatory uncertainty.

The constant $A_1^{(\omega)}$ and the investment threshold P_{SR} are found, in general, by value matching and smooth pasting conditions, so that W_{SR} is a continuous functions, with first order derivative for all possible values of P (see Øksendal & Sulem (2005)).

Next, we derive the value function and the investment thresholds for the aforementioned FIT schemes, without and with regulatory uncertainty, using the results of this section. The minimum price guarantee is a special case of the sliding premium, when the cap $C \rightarrow \infty$. Moreover, the fixed price is also special case of the sliding premium, when the value of the cap is equal to the value of the floor (i.e., $C = F$). For this reason, as we will see in the following sections, we derive first the results for the sliding premium, and then use these results to derive the other two regimes. The fixed premium needs to be studied separately, as it is not a special case of the sliding premium.

4 Investment decision

In this section, we derive the value function and the optimal investment trigger for each FIT scheme, where we first present the derivation of a scenario without regulatory uncertainty and then derive the equivalent function and trigger for the case with regulatory uncertainty.

We start analyzing the policy scheme called *sliding premium*, for which we present the derivations for the value function and investment trigger in more detail. The other two types of policy schemes, namely the *minimum price guarantee* and the *fixed price*, may be seen as special cases of the sliding premium; hence, we omit some details of the derivation. In Appendix B, we present the proofs that the minimum price guarantee and the fixed-price FIT are a special case of the sliding premium, letting $C \rightarrow \infty$ for the minimum price guarantee case and $C = F$ for the fixed-price FIT case. Finally we present the *fixed premium*, which is a different type of FIT when compared to the first three policy schemes.

4.1 Sliding premium

We consider a sliding-premium FIT with the following remuneration conditions: (i) the producer receives a price floor F when the market price is below the price floor, (ii) the producer receives a price cap C , where $C \geq F$, when the market price is above the price cap, and (iii) the producer sells energy for the electricity market price P when the market price lies between F and C .

Regarding the notation, we denote the payoff upon investment, the value function, and the investment threshold by V_C, W_C and P_C^* , respectively. As we also include the derivation of the same quantities under regulatory uncertainty, we use $V_C^{(\omega)}, W_C^{(\omega)}$, and $P_C^{*(\omega)}$ to denote the payoff upon investment, the value function, and the investment threshold when the price floor is ωF and the price cap is ωC . Finally, W_{CR} and P_{CR}^* denote the value function and investment threshold under regulatory uncertainty.

The instantaneous profit function of the renewable energy project with a sliding premium is given by:

$$\Pi_C(P) = \text{Min}(\text{Max}(P, F), C)Q \quad (15)$$

Next, we present the results concerning the investment thresholds for both cases, namely without and with regulatory uncertainty.

No regulatory uncertainty

We build on the work from Adkins, Paxson, Pereira & Rodrigues (2019) in order to derive the sliding premium and extend it in order to model a policy change before the project starts, with a Poisson process. In the above paper, the authors provide the value of the project with a perpetual sliding premium, given by:

$$V_{CP}(P) = \begin{cases} E_1 P^{\beta_1} + \frac{FQ}{r} & \text{for } P < F \\ G_1 P^{\beta_1} + G_2 P^{\beta_2} + \frac{PQ}{r - \mu} & \text{for } F \leq P < C \\ H_2 P^{\beta_2} + \frac{CQ}{r} & \text{for } P \geq C \end{cases} \quad (16)$$

where:

$$E_1 = \frac{(F^{1-\beta_1} - C^{1-\beta_1})Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) < 0 \quad (17)$$

$$G_1 = -\frac{C^{1-\beta_1}Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) < 0 \quad (18)$$

$$G_2 = \frac{F^{1-\beta_2}Q}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu} \right) > 0 \quad (19)$$

$$H_2 = \frac{(F^{1-\beta_2} - C^{1-\beta_2})Q}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu} \right) < 0 \quad (20)$$

We calculate E_1, G_1, G_2 , and H_2 by equating the values and derivatives because $V_{MP}(P)$ must be continuously differentiable in P . In addition, β_1 is presented in (7) and β_2 is:

$$\beta_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} - \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2} \right)^2 + \frac{2r}{\sigma^2} \right)^{\frac{1}{2}} < 0. \quad (21)$$

Moving on to the finite case ($T < \infty$), we start by deriving the value received upon investment (i.e, the value of the project), as defined in (4).

Proposition 1 *The value of the project with a finite sliding premium is given by:*

$$V_C(P) = V_{CP}(P) - S_C(P) + \frac{PQ}{r - \mu} e^{-(r-\mu)T} \quad (22)$$

where

$$\begin{aligned} S_C(P) = & E_1 P^{\beta_1} \Phi(-d_{\beta_1}(P, F)) + \frac{FQ}{r} e^{-rT} \Phi(-d_0(P, F)) \\ & + G_1 P^{\beta_1} (\Phi(d_{\beta_1}(P, F)) - \Phi(d_{\beta_1}(P, C))) + G_2 P^{\beta_2} (\Phi(d_{\beta_2}(P, F)) - \Phi(d_{\beta_2}(P, C))) \\ & + \frac{PQ}{r - \mu} e^{-(r-\mu)T} (\Phi(d_1(P, F)) - \Phi(d_1(P, C))) \\ & + H_2 P^{\beta_2} \Phi(d_{\beta_2}(P, C)) + \frac{CQ}{r} e^{-rT} \Phi(d_0(P, C)) \end{aligned} \quad (23)$$

where, in the above equations, $\Phi(\cdot)$ denotes the standard normal cumulative distribution, with

$$d_\beta(P, X) = \frac{\ln \frac{P}{X} + \left(\mu + \sigma^2 \left(\beta - \frac{1}{2} \right) \right) T}{\sigma \sqrt{T}}, \text{ for } \beta \in \{0, 1, \beta_1, \beta_2\}. \quad (24)$$

Proof. The value of the project with finite duration is equal to the value of the project with a sliding premium minus the value of the project with a delayed perpetual sliding premium (a sliding premium that starts in the future moment T) plus the expected value of the total profit after the end of the subsidized contract.

Equation (23) corresponds to the second term. For more details see the work from Adkins, Paxson, Pereira & Rodrigues (2019). ■

Therefore, we can present the value of the option and the investment threshold.

Proposition 2 *The value of the investment option in a project with a sliding premium is given by:*

$$W_C(P) = \begin{cases} (V_C(P_C^*) - I) \left(\frac{P}{P_C^*} \right)^{\beta_1} & \text{for } P < P_C^* \\ V_C(P) - I & \text{for } P \geq P_C^* \end{cases} \quad (25)$$

where the investment threshold, P_C^* , is the numerical solution of the following equation:

$$\beta_1 (V_C(P_C^*) - I) - \frac{\partial V_C(P_C^*)}{\partial P_C^*} P_C^* = 0 \quad (26)$$

The solution to this equation is presented in Appendix A.1. The solution of the investment threshold P_C^* , computed using (26), can only be found using numerical methods. Therefore, one may ask about the existence of admissible and uniqueness of these solutions. We do not provide proof of existence and uniqueness of solutions, but test a range of different values for the parameters, such as the base-case parameters in Section 5, and we were always able to find numerical solutions with the desired accuracy. This is also the case for the other regimes, with and without regulatory uncertainty. Although these equations are, in general, highly non-linear, again our tests suggest that any mathematics solver can find numerical solutions.

Regulatory uncertainty

Next, we follow similar steps to derive the investment threshold, but now for the scenario with regulatory uncertainty. According to (10), we need to solve the following differential equation:

$$\mu P \frac{\partial W_{CR}(P)}{\partial P} + 0.5\sigma^2 P^2 \frac{\partial^2 W_{CR}(P)}{\partial P^2} - rW_{CR}(P) + \lambda[J_1^{(\omega)} P^{\beta_1} - W_{CR}(P)] = 0. \quad (27)$$

where $J_1^{(\omega)}$ refers to the first branch of (25), which accounts for the value of the investment option in a project with a sliding premium with cap $\omega_c C$ and floor ωF . Hence:

$$J_1^{(\omega)} = (V_C^{(\omega)}(P_C^{*(\omega)}) - I) \left(\frac{1}{P_C^{*(\omega)}} \right)^{\beta_1} \quad (28)$$

where $P_C^{*(\omega)}$ is the correspondent of P_C^* , given by (26), when the price floor is ωF and the price cap is $\omega_c C$. The general solution of (27) is $K_1 P^{\eta_1} + J_1^{(\omega)} P^{\beta_1}$.

Note that ω and ω_c are smaller or equal to 1, consequently $\omega F \leq F$ and $\omega_c C \leq C$. We can thus conclude that $P_C^* < P_C^{*(\omega)}$. In other words, a smaller price floor and price cap leads to a higher investment threshold, because an investor that is still waiting to invest when the price floor is F and the price cap is C , will certainly be waiting to invest when the price floor and the price cap are lower (i.e., equal to ωF and $\omega_c C$).

Finally, we are able to present the value function and the investment threshold for this case.

Proposition 3 *The value of the option with a sliding-premium FIT scheme and regulatory uncertainty is given by:*

$$W_{CR}(P) = \begin{cases} (V_C(P_{CR}^*) - I - J_1^{(\omega)} P_{CR}^{*\beta_1}) \left(\frac{P}{P_{CR}^*} \right)^{\eta_1} + J_1^{(\omega)} P^{\beta_1} & \text{for } P < P_{CR}^* \\ V_C(P) - I & \text{for } P \geq P_{CR}^* \end{cases} \quad (29)$$

The investment threshold P_{CR}^* is the solution of the following equation, that must be solved numerically:

$$\eta_1 (V_C(P_{CR}^*) - I - J_1^{(\omega)} P_{CR}^{*\beta_1}) + \beta_1 J_1^{(\omega)} P_{CR}^{*\beta_1} - \frac{\partial V_C(P_{CR}^*)}{\partial P_{CR}^*} P_{CR}^* = 0 \quad (30)$$

This equation results in three equations that are presented in Appendix A.1.

Now we present the two regimes that may be seen as special cases of the sliding premium.

4.1.1 Minimum price guarantee FIT

A FIT with a minimum price guarantee (Barbosa, Ferrão, Rodrigues & Sardinha 2018) uses a price-floor regime. In this scheme, an investor either (i) receives a fixed amount when the market price is below the price floor, or (ii) sells energy for the market price when the market price is above the price floor. As mentioned above, the price-floor regime is a special case of the sliding premium when C goes to ∞ .

The instantaneous profit function of the renewable energy project with a minimum price guarantee is:

$$\Pi_M(P) = \text{Max}(P, F)Q \quad (31)$$

where F is a minimum price guarantee due to a FIT contract, and Q is the quantity of energy produced.

No regulatory uncertainty

Following the same reasoning of the sliding premium, the value of the project with a finite minimum guarantee is given by:

$$V_M(P) = V_{MP}(P) - S_M(P) + \frac{PQ}{r - \mu} e^{-(r-\mu)T} \quad (32)$$

where $V_{MP}(P)$ is the value of the perpetual minimum price guarantee contract, $S_M(P)$ is the value of the project with a delayed perpetual minimum price guarantee contract (i.e., a minimum price guarantee contract that starts in the future moment T), and $\frac{PQ}{r-\mu}e^{-(r-\mu)T}$ is the perpetual discounted profit from selling at market prices.

As a consequence of Proposition (1), letting $C \rightarrow \infty$, it follows that the value of the perpetual minimum price guarantee contract, V_{MP} , is given by:

$$V_{MP}(P) = \begin{cases} L_1 P^{\beta_1} + \frac{FQ}{r} & \text{for } P < F \\ M_2 P^{\beta_2} + \frac{PQ}{r-\mu} & \text{for } P \geq F \end{cases} \quad (33)$$

where

$$L_1 = \frac{QF^{1-\beta_1}}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) > 0 \quad (34)$$

$$M_2 = \frac{QF^{1-\beta_2}}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu} \right) > 0 \quad (35)$$

with L_1 is derived from (17) letting $C = \infty$, and $M_2 = G_2$ is derived from (19). See Proposition (11) of Appendix B.

Moreover, in (23) we let again $C = \infty$, and using the properties of the normal distribution, we conclude that

$$\begin{aligned} S_M(P) = & L_1 P^{\beta_1} \Phi(-d_{\beta_1}(P, F)) + \frac{FQ}{r} e^{-rT} \Phi(-d_0(P, F)) \\ & + M_2 P^{\beta_2} \Phi(d_{\beta_2}(P, F)) + \frac{PQ}{r-\mu} e^{-(r-\mu)T} \Phi(d_1(P, F)) \end{aligned} \quad (36)$$

Finally, as a consequence of Proposition (2), and in view of these quantities, the next result holds.

Proposition 4 *The value of the option to invest with a minimum price guarantee design and the investment threshold are:*

$$W_M(P) = \begin{cases} (V_M(P_M^*) - I) \left(\frac{P}{P_M^*} \right)^{\beta_1} & \text{for } P < P_M^* \\ V_M(P) - I & \text{for } P \geq P_M^* \end{cases} \quad (37)$$

where P_M^* is the solution of

$$\beta_1 (V_C(P_M^*) - I) - \frac{\partial V_C(P_M^*)}{\partial P_M^*} P_M^* = 0 \quad (38)$$

which in this case leads to two equations presented in Appendix A.2, that need to be solved using numerical methods.

We note that in this case the investment threshold P_M^* is the solution of one of the two equations of (38), depending on the relative ordering of P_M^* and F . This is a direct consequence of (31), as the instantaneous profit function depends also on the relative ordering of the price P and the minimum price guarantee F , which impacts of the expression for the value of the project, as shown in (33). Therefore, when one is deriving the investment threshold P_M^* , we have two possible

cases for the value matching and smoothing pasting conditions, depending on what instance of the value of the project we are using.

Regulatory uncertainty

In a similar way to what we have considered in the previous sections, we also consider the case that the minimum price guarantee F can be affected by a policy change before the project starts. As the reasoning is similar to the one presented previously, we omit further comments and present the results for a scenario with a finite minimum price guarantee contract and regulatory uncertainty.

Proposition 5 *The value of the option with a minimum price guarantee and regulatory uncertainty is given by:*⁶

$$W_{MR}(P) = \begin{cases} (V_M(P_{MR}^*) - I - N_1^{(\omega)} P_{MR}^{*\beta_1}) \left(\frac{P}{P_{MR}^*} \right)^{\eta_1} + N_1^{(\omega)} P^{\beta_1} & \text{for } P < P_{MR}^* \\ V_M(P) - I & \text{for } P \geq P_{MR}^* \end{cases} \quad (39)$$

where

$$N_1^{(\omega)} = \left(V_M^{(\omega)}(P_M^{*(\omega)}) - I \right) \left(\frac{1}{P_M^{*(\omega)}} \right)^{\beta_1} \quad (40)$$

The investment threshold P_{MR}^* is the solution of the following equation, that must be solved numerically:

$$\eta_1 (V_M(P_{MR}^*) - I - N_1^{(\omega)} P_{MR}^{*\beta_1}) + \beta_1 N_1^{(\omega)} P_{MR}^{*\beta_1} - \frac{\partial V_M(P_{MR}^*)}{\partial P_{MR}^*} P_{MR}^* = 0 \quad (41)$$

This equation results in three equations that are presented in Appendix A.2.

4.1.2 Fixed-price FIT

In this regime, the renewable energy producer has a fixed-tariff contract, where the firm receives F for a period of time T . The fixed-price scheme is a special case of the sliding premium when C is equal to F . Among all FIT designs, the fixed-price FIT is the most widely used FIT scheme around the world. For instance, fixed-price FITs have been offered in Germany, France, Portugal, Canada, and among other countries (Couture, Kreycik & Williams 2010).

The value of the project has a fixed-tariff contract with a finite duration T . After time T , the renewable energy producer sells the energy for the market price P . Hence, after investment, the firm gets the following expected value in (2):

$$V_F(P) = E \left[\int_0^T FQ e^{-rt} dt + \int_T^{+\infty} P_t Q e^{-rt} dt \middle| P_0 = P \right] = \frac{FQ}{r} (1 - e^{-rT}) + \frac{PQ}{r - \mu} e^{-(r-\mu)T}. \quad (42)$$

In Proposition (12) of Appendix B we present a formal proof of such result, using the results from the sliding premium.

No regulatory uncertainty

In view of Proposition (2), with $F = C$, it follows that

⁶The general option value function is $R_1 P^{\eta_1} + N_1^{(\omega)} P^{\beta_1}$.

Proposition 6 *The value of the investment option with a fixed price design is given by:*⁷

$$W_F(P) = \begin{cases} (V_F(P_F^*) - I) \left(\frac{P}{P_F^*} \right)^{\beta_1} & \text{for } P < P_F^* \\ V_F(P) - I & \text{for } P \geq P_F^* \end{cases} \quad (43)$$

where the investment threshold P_F^* is equal to:

$$P_F^* = \frac{\beta_1}{(\beta_1 - 1)} \frac{r - \mu}{Q e^{-(r-\mu)T}} \left(I - \frac{FQ}{r} (1 - e^{-rT}) \right). \quad (44)$$

We note that in this case, contrary to the previous cases, we are able to find a closed expression for the investment threshold.

Regulatory uncertainty

If regulatory uncertainty is present, then it follows from the previous results that the value function and investment threshold are given as follows.

Proposition 7 *The value of the investment option with a fixed price scheme and regulatory uncertainty is given by:*⁸

$$W_{FR}(P) = \begin{cases} \left(V_F(P_{FR}^*) - I - S_1^{(\omega)} P_{FR}^{\beta_1} \right) \left(\frac{P}{P_{FR}^*} \right)^{\eta_1} + S_1^{(\omega)} P^{\beta_1} & \text{for } P < P_{FR}^* \\ V_F(P) - I & \text{for } P \geq P_{FR}^* \end{cases} \quad (45)$$

where the investment threshold P_{FR}^* is the solution of the following equation, which needs to be solved using numerical methods:

$$-(\eta_1 - \beta_1) S_1^{(\omega)} P_{FR}^{\beta_1} + (\eta_1 - 1) \frac{P_{FR}^* Q}{r - \mu} e^{-(r-\mu)T} + \eta_1 \left(\frac{FQ}{r} (1 - e^{-rT}) - I \right) = 0. \quad (46)$$

4.2 Fixed-premium FIT

Next, we analyze a fixed-premium contract, whereby the firm receives a bonus F over the market price. Fixed-premium FIT policies have been offered in countries such as Spain, the Czech Republic and the Netherlands (Couture, Kreycik & Williams 2010). In fact, Spain and the Czech Republic let investors choose between a fixed-price FIT and a fixed-premium FIT.

For this contract, the profit function is given as follows:

$$\Pi_P(P) = (P + F)Q \quad (47)$$

where F is a premium over the electricity market price. It follows that this regime cannot be seen as a special case of a sliding premium.

If the firm invests with a current price P , the firm gets the following expected value:

$$V_P(P) = E \left[\int_0^T (P + F)Q e^{-rt} dt + \int_T^{+\infty} PQ e^{-rt} dt \middle| P_0 = P \right] = \frac{PQ}{r - \mu} + \frac{FQ}{r} (1 - e^{-rT}). \quad (48)$$

No regulatory uncertainty

Using the results in Section 3, we obtain the following value of the investment option for this type of contract.

⁷The general option value function is $S_1 P^{\beta_1}$.

⁸The general option value function is $U_1 P^{\eta_1} + S_1^{(\omega)} P^{\beta_1}$.

Proposition 8 *The value of the investment option when the producer has a fixed-premium FIT contract is given by:*⁹

$$W_P(P) = \begin{cases} (V_P(P_P^*) - I) \left(\frac{P}{P_P^*}\right)^{\beta_1} & \text{for } P < P_P^* \\ V_P(P) - I & \text{for } P \geq P_P^* \end{cases} \quad (49)$$

where the investment threshold P_P^* is given by:

$$P_P^* = \frac{\beta_1}{\beta_1 - 1} \frac{r - \mu}{Q} \left(I - \frac{FQ}{r} (1 - e^{-rT}) \right). \quad (50)$$

Regulatory uncertainty

If we consider uncertainty in the retraction of the subsidy, a straightforward application of the results of Section 3 lead to the following.

Proposition 9 *The value of the investment option with a fixed-premium FIT scheme and regulatory uncertainty is given by:*¹⁰

$$W_{PR}(P) = \begin{cases} \left(V_F(P_{PR}^*) - I - V_1^{(\omega)} P_{PR}^{\beta_1} \right) \left(\frac{P}{P_{PR}^*} \right)^{\eta_1} + V_1^{(\omega)} P^{\beta_1} & \text{for } P < P_{PR}^* \\ V_F(P) - I & \text{for } P \geq P_{PR}^* \end{cases} \quad (51)$$

where the investment threshold P_{PR}^* is the solution of the following equation, which needs to be solved numerically.

$$-(\eta_1 - \beta_1) V_1^{(\omega)} P_{PR}^{\beta_1} + (\eta_1 - 1) \frac{Q}{r - \mu} P_{PR}^* + \eta_1 \left(\frac{FQ}{r} (1 - e^{-rT}) - I \right) = 0. \quad (52)$$

5 Analytical and numerical study

In this section, we study the influence of some parameters on the investment thresholds of the FIT schemes addressed in this paper. In some cases, we are able to present analytical results and corresponding plots of the thresholds; whereas in other cases, we only present the plots based on numerical results for a given set of parameter values. For the latter case, we have performed many other tests with other parameter values, besides the one presented in this section, and the results are qualitatively the same.

For the numerical study, we use a typical European onshore wind farm with 25 wind turbines (Enevoldsen & Valentine 2016), although our FIT models do not have any technology-specific characteristics. The investment cost of each turbine is 1.5 Million Euros / MW (EWEA 2009) and each turbine has a 2MW capacity. We also assume that the wind turbine's capacity factor is 30%, which is a reasonable estimate according to EWEA (2009).

In order to simplify the analysis, we calculate the investment threshold for a single turbine but the results can be easily extended for any number of turbines. We also assume that all parameters have annualized values. For instance, a fixed-price FIT with an F equal to €25 / MWh generates an annual revenue of €131,400.00 (i.e., 30 % x 2 MWh x €25 / MWh x 24 hours x 365 days).

In addition, we use the same values of Ritzenhofen & Spinler (2016) for the GBM parameters, which are based on real data. Table 1 summarizes the base-case parameters of the numerical study in this section. In particular for the sliding premium, we assume that the annual revenue from the price cap is equal to €300,000.00 (\approx €57.08 / MWh).

⁹The general option value function is $V_1 P^{\beta_1}$.

¹⁰The general option value function is $W_1 P^{\eta_1} + V_1^{(\omega)} P^{\beta_1}$.

Table 1: Base-case parameters used to calculate the thresholds

r	risk-free rate	5%
F	tariff	€25 / MWh
T	finite duration of FIT	15 years
μ	deterministic drift	0%
σ	volatility	19%
I	total investment cost	€3 Millions
ω	the reduction of F is $(1 - \omega)$	80%
ω_C	the reduction of C is $(1 - \omega_C)$	100%
λ	mean arrival rate of a jump event	0.5

5.1 The effect of regulatory uncertainty

This section presents the results of the comparative statics of the two parameters related to regulatory uncertainty (i.e., λ and ω). In particular, we derive the partial derivatives of the optimal investment thresholds with respect to λ and ω in order to determine whether the thresholds increase or decrease, by manipulating equations that define implicitly these investment thresholds (as in the case of regulatory uncertainty, the investment thresholds for all the regimes are defined implicitly, by some non-linear equation). The proofs are presented in Appendix C, and are somehow simplified, as they follow from long calculations.

Proposition 10 *When there is regulatory uncertainty, the investment thresholds for all the four schemes considered in this paper decrease with λ and increase with ω .*

Therefore, investment is anticipated when it is more likely that a reduction of the tariff occurs, because investors prefer to anticipate the investment decision in order to obtain a higher tariff for a longer period. Figure 1 illustrates this behavior, for different values of the parameter λ . We also include the investment threshold in a free-market condition (i.e., P_W^*),¹¹ where investors do not have any FIT policies available. Note that, for the sliding premium, we do not consider changes in the price cap (i.e., $\omega_C = 1$) due to regulatory uncertainty. We analyze the effect of regulatory uncertainty on the price cap later in this section.

An interesting result in Figure 1 is that increasing λ generates a higher reduction in the fixed-price and fixed-premium thresholds than in the price-floor and sliding-premium thresholds. The intuition behind this effect is due to the reduction and how it affects the four FIT policies. While the reduction in the fixed-price and fixed-premium policies always leads to a revenue loss, the price-floor and sliding-premium regimes only suffer a revenue loss when $P < F$. In addition, despite the sliding-premium and price-floor thresholds appear to be equally affected by λ , we have calculated the difference between the thresholds and it is not constant as λ increases.

A similar effect occurs if the reduction of the tariff is larger. Figure 2 illustrates such behavior. The plot of the investment threshold of the sliding premium assumes that the reduction only affects the price floor. From Figure 2, we can observe that all the investment thresholds decrease as ω decreases. This is due to the fact that lower values of ω produce higher reductions in the tariff, and consequently a lower expected profit. These potential losses generate lower investment thresholds because investors decide to accelerate investment in order to obtain a higher tariff before the jump event occurs. In addition, the effect of ω is greater in the fixed-price and fixed-premium FIT schemes, as shown in Figure 2, because of the same reason explained for the parameter λ .

Although we assume in Figure 2 that a policy-making decision could only reduce the price floor in the sliding premium, we know that policy uncertainty may also affect the price cap. Hence,

¹¹We calculate P_W^* with the threshold of the fixed-premium where the tariff F is equal to 0.

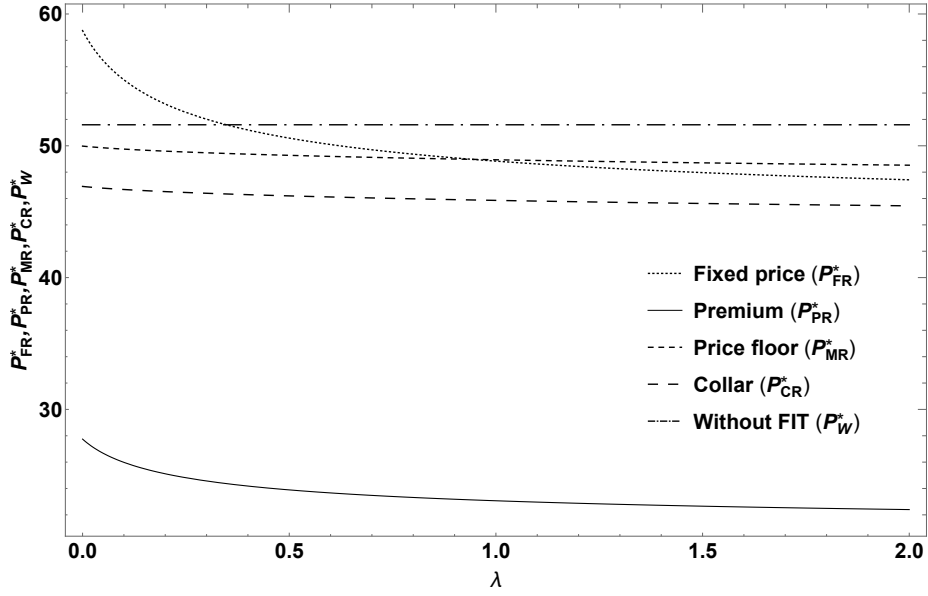


Figure 1: Triggers P_{FR}^* , P_{PR}^* , P_{MR}^* and P_{CR}^* as a function of λ

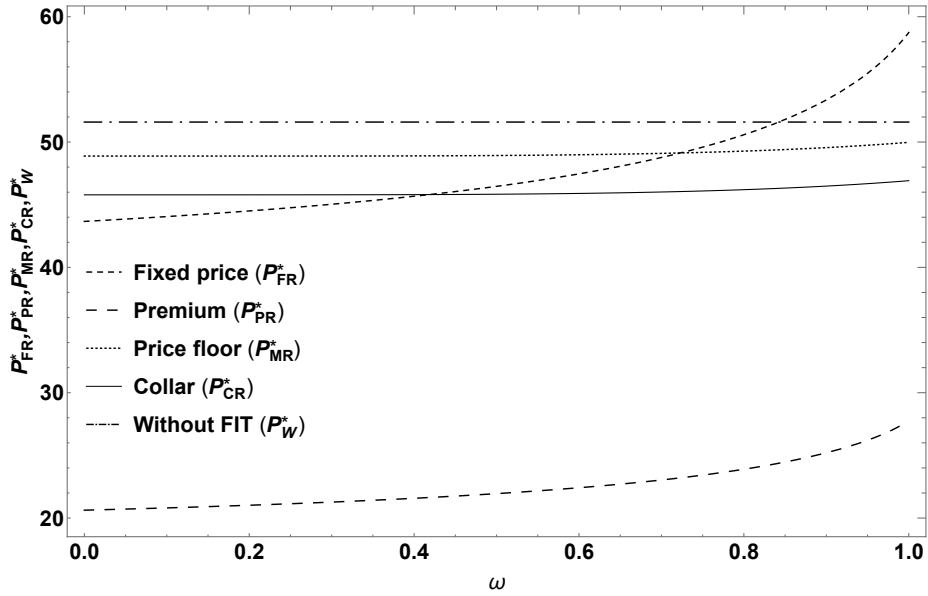


Figure 2: Triggers P_{FR}^* , P_{PR}^* , P_{MR}^* and P_{CR}^* as a function of ω

Figures 3a and 3b present the investment threshold when a policy reduction affects the price cap. We assume that the price cap may be reduced to $\omega_C C$ when a jump event occurs with a probability λdt . In Figure 3a, we observe that the investment threshold decreases as ω_C decreases, thus accelerating the investment decision. In addition, Figure 3b plots the investment threshold when $\omega = 1$ and $\omega_C = 0.8$, and we can see that the threshold reduces as λ increases. Hence, investment is accelerated when a reduction is more likely to occur.

Another interesting observation occurs when we compare the sliding-premium threshold in Figure 1, where $\omega = 0.8$ and $\omega_C = 1$, with Figure 3b, where $\omega = 1$ and $\omega_C = 0.8$. As λ increases, we observe that the investment threshold has a larger reduction when the policymaker reduces the price cap, as observed in Figure 3b, than the price floor, as shown in Figure 1. In a similar comparison, we observe a larger reduction in the investment threshold in Figure 3a, where ω_C varies in the interval $[0, 1]$, than the reduction in the sliding-premium threshold in Figure 2, where ω varies in the interval $[0, 1]$. In summary, these plots show that the price cap reduction has a higher impact on investment threshold than the price floor reduction.

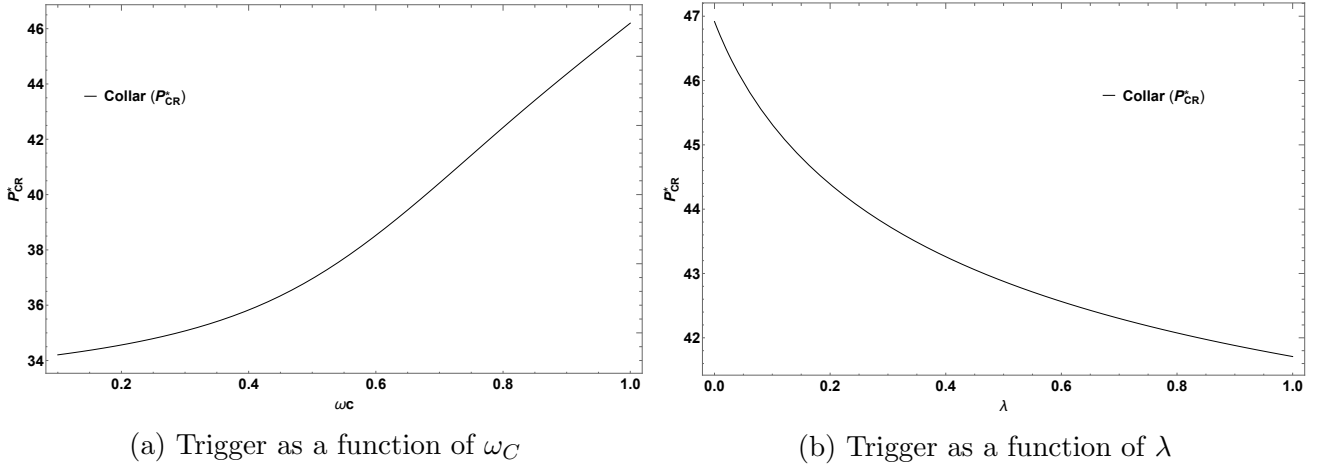


Figure 3: Trigger P_{CR}^* as a function of ω_C and λ

5.2 Comparison of the tariff schemes

This section presents a numerical analysis of the investment thresholds of the FIT policies under regulatory uncertainty when key parameters change, such as the value of the tariff and the volatility.

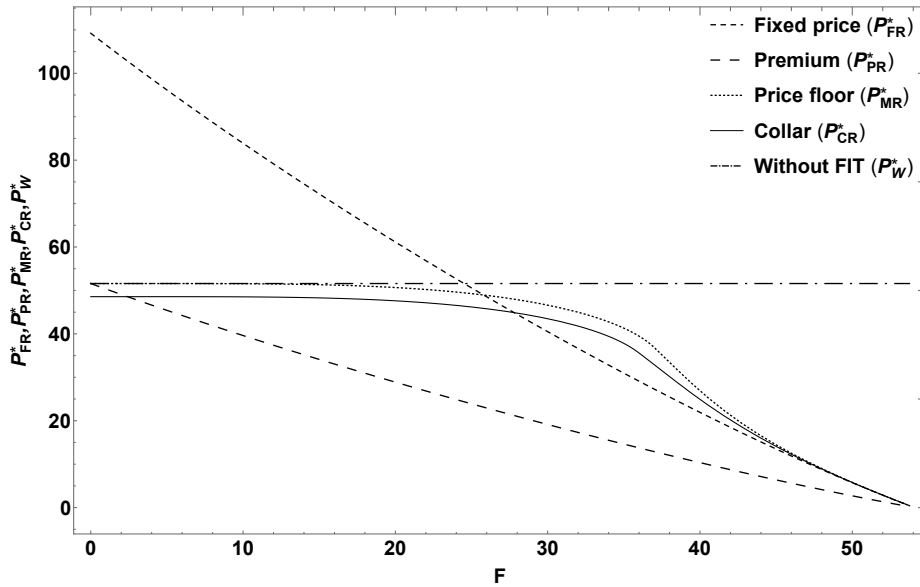


Figure 4: Thresholds P_{FR}^* , P_{PR}^* , P_{MR}^* and P_{CR}^* as a function of F

Figure 4 presents the investment thresholds for the four different FIT policies as a function of the tariff F . The plots show that the investment thresholds of the FIT policies decrease as F increases; in other words, the decision to invest is accelerated when F increases¹². In the Appendix we find the analytical proof of such result for the fixed price and fixed premium (with and without regulatory uncertainty).

We also observe that the thresholds for the fixed-premium regime, price-floor regime, and sliding premium are lower than the investment threshold in a free-market condition. In fact, these are expected results for policymakers because a key goal of a price-based incentive, such as a FIT, should be to accelerate the investment decision. The only exception is the fixed-price regime for values of F approximately lower than $\text{€}25/\text{MWh}$, where the investment threshold in a free-market condition is below the investment threshold of the fixed-price regime. This result

¹²The same result holds for a scenario without regulatory uncertainty

suggests that investors prefer the free-market condition to a low remuneration from the fixed-price FIT. Hence, policymakers should offer values of the tariff with a fixed-price scheme greater than this point. In other words, this is the minimum value of the tariff that policymakers should offer within a fixed-price FIT contract.

The plots of the investment threshold of the sliding-premium and price-floor regimes in Figure 4 present two relevant results for policymakers. First, the price-floor regime is a special case of the sliding premium as shown in Figure 5, whereby the investment threshold of the sliding premium rapidly converges to the price-floor regime as we increase the value of the cap C ¹³. Second, we observe from Figure 4 that the sliding-premium threshold is below the price-floor threshold when both regimes have the same price floor value. This result of accelerating the investment decision is due to the cap, especially for lower values of the price floor. There are two probable explanations for this result. First, investors are anticipating the investment decision in order to avoid the cap, and hence prefer to start the investment earlier when the market price is lower. Second, investors defer investment under the price-floor regime because they may hope for higher prices in the future. However, from a policy-making perspective, this result suggests that the sliding premium is a better policy than the price-floor regime because it accelerates the investment while avoiding excessive earnings for producers or excessive payments for consumers. In addition, we analytically prove that the value of the project with a price-floor regime is always greater than the value of the project with a sliding premium in Appendix B at Proposition 13. These are expected results because an investor should have a higher profit without the price cap.

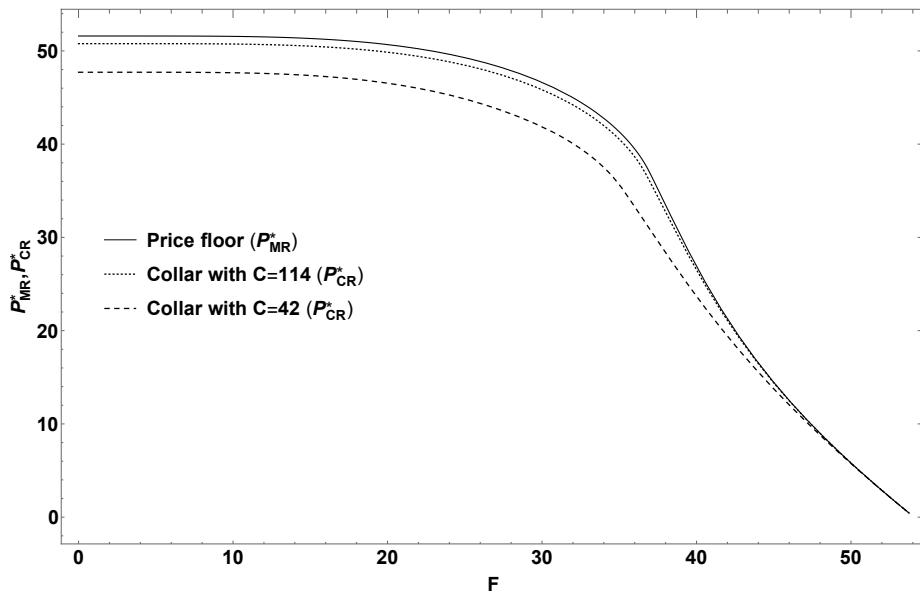


Figure 5: Triggers P_{MR}^* and P_{CR}^* as a function of the tariff F for different values of the cap C

In Figure 6, we present the plots of the investment threshold of the sliding premium as a function of the cap C , whereby the sliding-premium threshold in Figure 6a has $\omega = 0.8$ and $\omega_C = 1.0$ and the sliding-premium threshold in Figure 6b has $\omega = \omega_C = 0.8$. We also include the investment thresholds of the fixed price and minimum price guarantee in order to present three interesting properties of these FIT schemes. First, we observe that the sliding-premium threshold converges to the threshold of the minimum price guarantee as C increases in both Figures 6a and 6b. This result is consistent with Proposition 11. Second, we observe that the sliding-premium threshold and the fixed-price threshold meet when C is equal to F in Figure 6b, because $\omega = \omega_C = 0.8$. In other words, the thresholds meet because both FITs generate the same remuneration whether the policy change occurs (i.e., a producer receives $\omega_C C = \omega F$) or not occurs

¹³In Appendix B at Proposition 11 we prove that the value of the project with a sliding premium converges to a price-floor regime when $C \rightarrow +\infty$. Consequently, the thresholds of both regimes are the same when $C \rightarrow +\infty$.

(a producer receives $C = F$). However, the same does not occur in Figure 6a, because $\omega \neq \omega_C$. In this case, the thresholds are not the same when $C = F$, because both FITs generate different remunerations when the policy change occurs (recall that the fixed-price tariff is ωF while the sliding premium has a price floor equal to $\omega F = 0.8F$ and a cap equal to $\omega_C C = C$). Lastly, we observe that the sliding-premium threshold has a minimum point where C is approximately equal to 42 in Figure 6a and 39 in Figure 6b. Therefore, policymakers should not offer caps above this value.

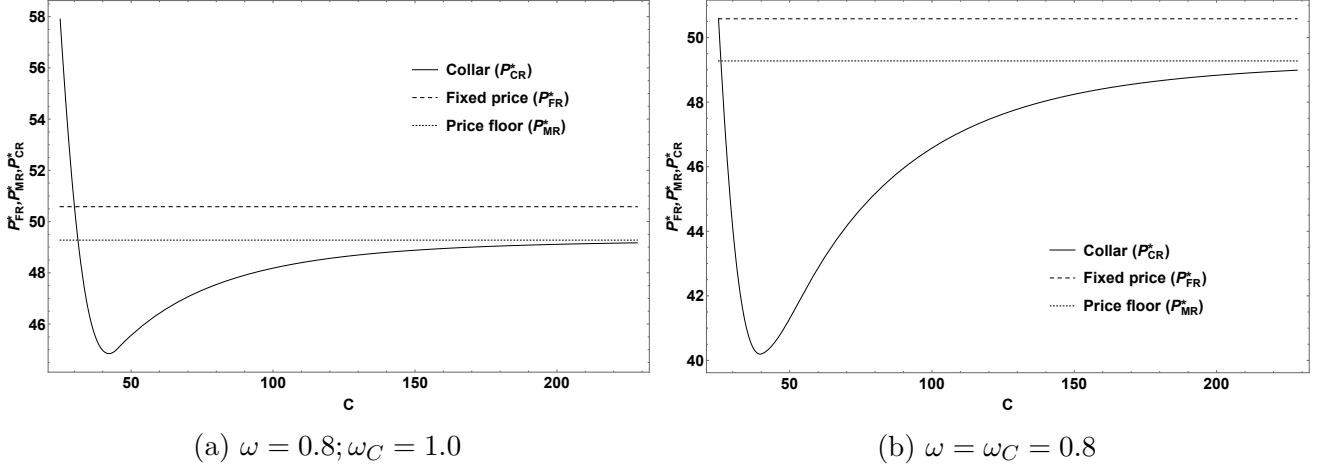


Figure 6: Threshold P_{CR}^* as a function of the price cap C

Figure 7 presents the plots of the investment thresholds for different values of the volatility σ . The results are consistent with the real options theory where higher volatilities increase the thresholds and consequently postpone the investment decision. Moreover, in the Appendix we prove analytically such result for the fixed-price and for the fixed-premium regimes, with and without regulatory uncertainty.

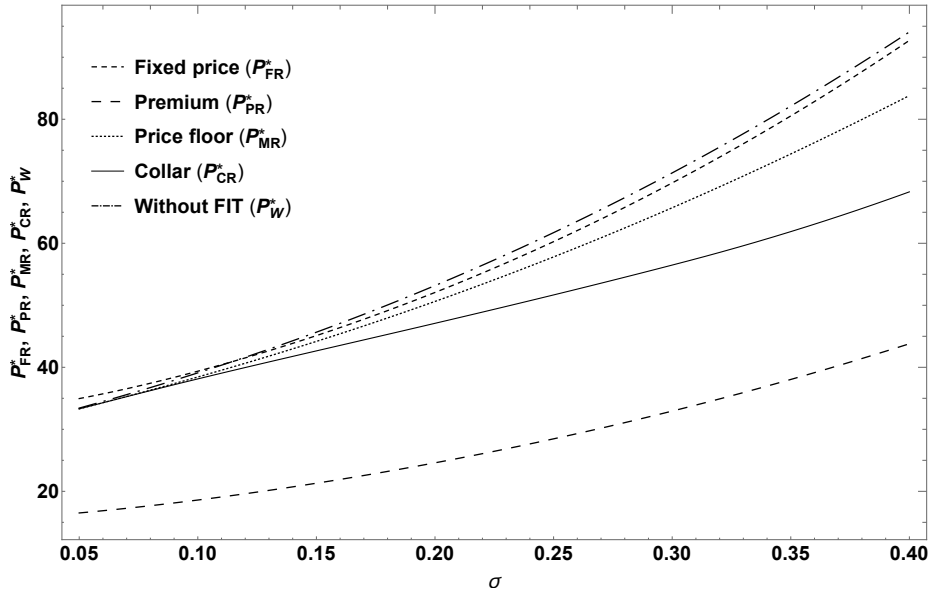
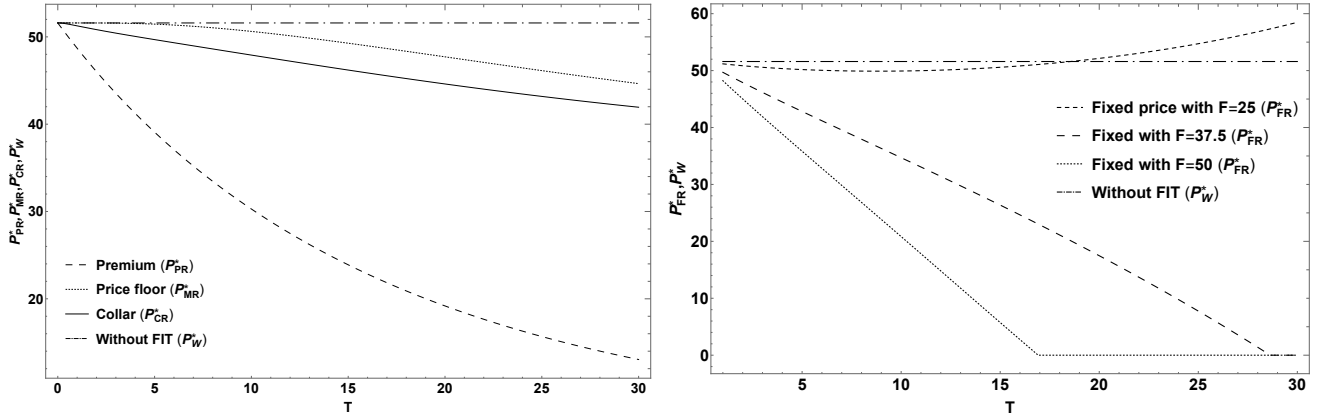


Figure 7: Thresholds P_{FR}^* , P_{PR}^* , P_{MR}^* and P_{CR}^* as a function of σ

In Figure 8, we present the plots of the investment thresholds for different values of the duration of the contract T . The fixed premium, the price floor and the sliding premium presented in Figure 8a accelerate the investment when policymakers increase the duration of the contract. However, the fixed-price regime is different when the tariff is low, as shown in Figure 8b. For a tariff equal to $\text{€}25/\text{MWh}$, note that the fixed-price FIT duration has a non-monotonic effect: it initially

accelerates investment and then it defers investment as we increase the duration of the contract. Figure 8b also shows that this effect does not occur for higher tariffs (i.e., €37.5/MWh and €50/MWh) because the investment is accelerated when the duration of the contract increases. Hence, policymakers should not use low tariffs in the fixed-price regime because it might generate an undesired behavior of postponing the investment decision.



(a) Fixed premium, Price floor and Sliding premium (b) Fixed price regime for different values of F

Figure 8: Investment threshold as function of T

From the previous figures in this section, one might draw a conclusion that the fixed-premium regime is the best FIT contract because it presents the lowest investment trigger. However, this is a misleading conclusion because the previous plots consider that all regimes have the same tariff value F . In particular, the fixed-premium regime considers that the remuneration is equal to the market price plus the tariff F , which generates a higher remuneration than all the other regimes. Figure 9 presents the values of the tariff that generate the same investment trigger. As expected, the fixed-premium plot is below all the other plots because a policymaker should use a smaller tariff for this regime in order to generate the same threshold as the other regimes. Figure 9 can also be used as a tool for policy-making because it presents the values of the tariff F that generate the same trigger for the four FIT policies.

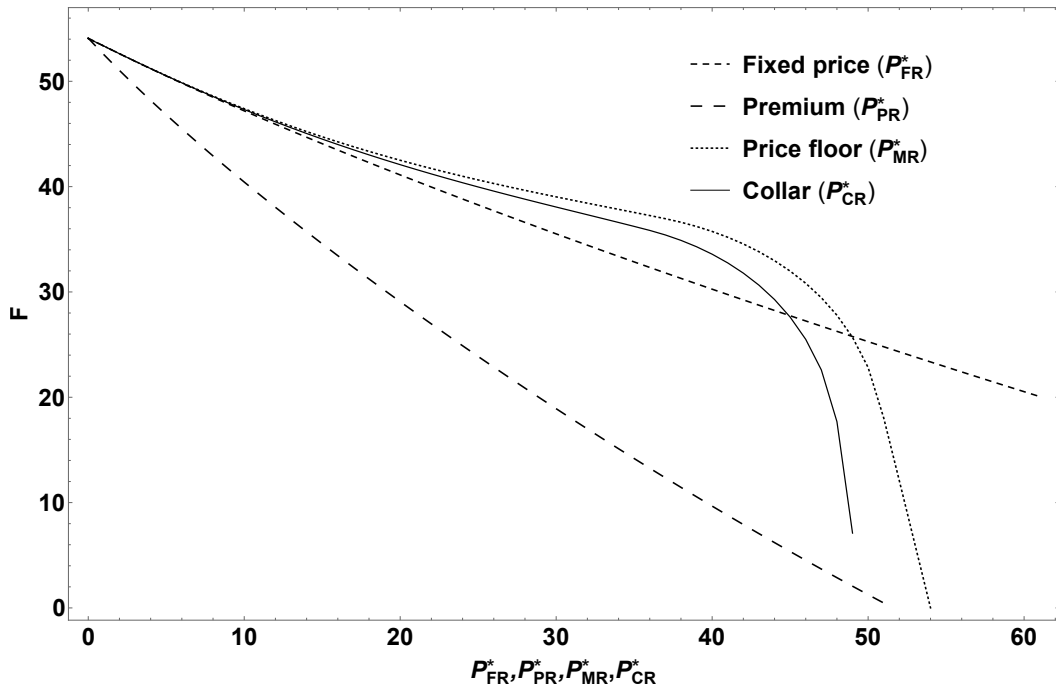


Figure 9: Feed-in tariff F as a function of the thresholds

6 Concluding remarks

This work analyzes two different feed-in premiums, namely a minimum price guarantee and a sliding premium. We also include the fixed-price FIT and fixed-premium FIT in the analysis, because these schemes have been widely analyzed within the scientific community. For each scheme, we use a semi-analytical real options framework in order to calculate the value of the project, the option value, and the optimal investment threshold. We also extend the models of each FIT scheme in order to include regulatory uncertainty, where we use a Poisson process to model an occasional reduction on the tariff before the project starts.

Regarding the effect of the regulatory uncertainty, the results show that investment is accelerated when a reduction of the tariff is more likely to occur, because investors are anticipating the investment decision in order to obtain a higher tariff. In addition, a higher probability of policy change generates a higher reduction in the fixed-price and fixed-premium thresholds than the thresholds of the price floor and the sliding premium. This effect is due to a revenue loss that always occurs in the fixed-price and fixed-premium schemes in the event of a policy change, while the price-floor and sliding-premium schemes only suffer a revenue loss when the market price is below the guarantee. Regarding the analysis of the tariff reduction, we also reach the same conclusions. Thus, a higher reduction of the tariff accelerates the investment. We also find that the effect of the tariff reduction is greater for the fixed-price and fixed-premium thresholds than the price-floor and sliding-premium thresholds.

This paper also presents several results for policy making. First, the sliding premium has an interesting property. The possibility of reducing only the cap leads to a lower threshold when compared with the same effect on the price floor. Hence, the sliding premium under the risk of regulatory uncertainty in the price cap has a higher impact on the investment threshold than the price floor.

Second, the thresholds of the fixed-premium regime, price-floor regime, and sliding premium are lower than the investment threshold in a free-market condition. In fact, this is an expected result, because these policy schemes are aimed at accelerating a renewable energy investment. However, the fixed-price regime only has a threshold below the free-market condition when the tariff is greater than a certain value. Consequently, policymakers should avoid offering low values of the tariff in the fixed-price regime.

Third, the results show that the sliding premium has a lower investment threshold than the price-floor regime, especially when the price floor assumes lower values. This could suggest that the sliding premium is a better policy because it accelerates investment and has the property of avoiding excessive earnings for producers or excessive payments for consumers.

Fourth, increasing the duration of the contract reduces the investment threshold of the fixed-premium regime, price-floor regime, and sliding premium. However, this effect does not occur in the fixed-price regime if the tariff is low. Lastly, we present an interesting tool for policy-making with our model, whereby policymakers can find the values of the tariff F that generate the same trigger for the four FIT policies.

The current paper can be extended in several ways. From a policy-making perspective, the welfare effects of the different FIT schemes are relevant. These include not only the budget costs but also the effects on the consumers' and producers' surpluses, as well as the environmental effects. Further research could also consider the optimal capacity choice of the renewable energy producer, following Bar-Ilan & Strange (1999) and Dangl (1999) for the monopoly case, and Huisman & Kort (2015) for the duopoly case, and Boomsma, Meade & Fleten (2012) and Chronopoulos, Hagspiel & Fleten (2016) for price-taker firms. Another interesting extension is the possibility of retroactive reduction of the tariff (after the investment occurs). Since we deal with finite-lived schemes, a numerical method is required to find the project value, as it becomes time-dependent (the value of the project depends upon when the FIT is reduced).

Acknowledgements

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A Equations for finding the triggers

In this section we present the equations that need to be solved numerically to obtain the triggers for investment for the sliding premium and minimum price guarantee FITs.

A.1 Sliding premium

For the case without regulatory uncertainty, Equation (26) results in following three equations:

$$\left\{ \begin{array}{l}
 -(\beta_1 - \beta_2) (G_2 (\Phi(d_{\beta_2}(P_C^*, F)) - \Phi(d_{\beta_2}(P_C^*, C))) \\
 \quad + H_2 \Phi(d_{\beta_2}(P_C^*, C))) P_C^{*\beta_2} \\
 + (\beta_1 - 1) \frac{P_C^* Q}{r - \mu} e^{-(r-\mu)T} (1 - (\Phi(d_1(P_C^*, F)) - \Phi(d_1(P_C^*, C)))) \\
 + \beta_1 \frac{FQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_C^*, F)))) \\
 - \beta_1 \left(\frac{CQ}{r} e^{-rT} (1 - \Phi(d_0(P_C^*, C))) + I \right) = 0 \quad \text{for } P_C^* < F \\
 \\
 (\beta_1 - \beta_2) (G_2 (1 - (\Phi(d_{\beta_2}(P_C^*, F)) - \Phi(d_{\beta_2}(P_C^*, C)))) \\
 \quad - H_2 \Phi(d_{\beta_2}(P_C^*, C))) P_C^{*\beta_2} \\
 + (\beta_1 - 1) \frac{P_C^* Q}{r - \mu} (1 + e^{-(r-\mu)T} (1 - (\Phi(d_1(P_C^*, F)) - \Phi(d_1(P_C^*, C)))) \\
 - \beta_1 \frac{FQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_C^*, F)))) \\
 - \beta_1 \left(\frac{CQ}{r} e^{-rT} \Phi(d_0(P_C^*, C)) + I \right) = 0 \quad \text{for } F \leq P_C^* < C \\
 \\
 -(\beta_1 - \beta_2) (G_2 (\Phi(d_{\beta_2}(P_C^*, F)) - \Phi(d_{\beta_2}(P_C^*, C))) \\
 \quad - H_2 (1 - \Phi(d_{\beta_2}(P_C^*, C)))) P_C^{*\beta_2} \\
 + (\beta_1 - 1) \frac{P_C^* Q}{r - \mu} e^{-(r-\mu)T} (1 - (\Phi(d_1(P_C^*, F)) - \Phi(d_1(P_C^*, C)))) \\
 - \beta_1 \frac{FQ}{r} e^{-rT} (1 - \Phi(d_0(P_C^*, F))) \\
 + \beta_1 \left(\frac{CQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_C^*, C)))) - I \right) = 0 \quad \text{for } P_C^* \geq C
 \end{array} \right. \quad (53)$$

For the case with regulatory uncertainty, Equation (30) results in following three equations:

$$\left\{ \begin{array}{l}
(\eta_1 - \beta_1) (E_1 \Phi(d_{\beta_1}(P_{CR}^*, F))) \\
\quad - G_1 (\Phi(d_{\beta_1}(P_{CR}^*, F)) - \Phi(d_{\beta_1}(P_{CR}^*, C))) - J_1^{(\omega)} P_{CR}^{*\beta_1} \\
-(\eta_1 - \beta_2) (G_2 (\Phi(d_{\beta_2}(P_{CR}^*, F)) - \Phi(d_{\beta_2}(P_{CR}^*, C))) \\
\quad + H_2 \Phi(d_{\beta_2}(P_{CR}^*, C))) P_{CR}^{*\beta_2} \\
+(\eta_1 - 1) \frac{P_{CR}^* Q}{r - \mu} e^{-(r-\mu)T} (1 - (\Phi(d_1(P_{CR}^*, F)) - \Phi(d_1(P_{CR}^*, C)))) \\
+\eta_1 \frac{FQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_{CR}^*, F)))) \\
-\eta_1 \left(\frac{CQ}{r} e^{-rT} (1 - \Phi(d_0(P_{CR}^*, C))) + I \right) = 0 \quad \text{for } P_{CR}^* < F \\
\\
-(\eta_1 - \beta_1) (E_1 (1 - \Phi(d_{\beta_1}(P_{CR}^*, F))) \\
\quad - G_1 (1 - (\Phi(d_{\beta_1}(P_{CR}^*, F)) - \Phi(d_{\beta_1}(P_{CR}^*, C)))) + J_1^{(\omega)} P_{CR}^{*\beta_1} \\
+(\eta_1 - \beta_2) (G_2 (1 - (\Phi(d_{\beta_2}(P_{CR}^*, F)) - \Phi(d_{\beta_2}(P_{CR}^*, C)))) \\
\quad - H_2 \Phi(d_{\beta_2}(P_{CR}^*, C))) P_{CR}^{*\beta_2} \\
+(\eta_1 - 1) \frac{P_{CR}^* Q}{r - \mu} (1 + e^{-(r-\mu)T} (1 - (\Phi(d_1(P_{CR}^*, F)) - \Phi(d_1(P_{CR}^*, C)))) \\
-\eta_1 \frac{FQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_{CR}^*, F)))) \\
-\eta_1 \left(\frac{CQ}{r} e^{-rT} \Phi(d_0(P_{CR}^*, C)) + I \right) = 0 \quad \text{for } F \leq P_{CR}^* < C \\
\\
-(\eta_1 - \beta_1) (E_1 \Phi(d_{\beta_1}(P_{CR}^*, F))) \\
\quad + G_1 (\Phi(d_{\beta_1}(P_{CR}^*, F)) - \Phi(d_{\beta_1}(P_{CR}^*, C))) + J_1^{(\omega)} P_{CR}^{*\beta_1} \\
+(\eta_1 - \beta_2) (G_2 (\Phi(d_{\beta_2}(P_{CR}^*, F)) - \Phi(d_{\beta_2}(P_{CR}^*, C))) \\
\quad - H_2 (1 - \Phi(d_{\beta_2}(P_{CR}^*, C)))) P_{CR}^{*\beta_2} \\
+(\eta_1 - 1) \frac{P_{CR}^* Q}{r - \mu} e^{-(r-\mu)T} (1 - (\Phi(d_1(P_{CR}^*, F)) - \Phi(d_1(P_{CR}^*, C)))) \\
-\eta_1 \frac{FQ}{r} e^{-rT} (1 - \Phi(d_0(P_{CR}^*, F))) \\
+\eta_1 \left(\frac{CQ}{r} (1 - e^{-rT} (1 - \Phi(d_0(P_{CR}^*, C)))) - I \right) = 0 \quad \text{for } P_{CR}^* \geq C
\end{array} \right. \quad (54)$$

A.2 Minimum price guarantee

For the case without regulatory uncertainty, Equation (38) results in the following two equations:

$$\left\{ \begin{array}{l} -(\beta_1 - \beta_2)M_2P_M^{*\beta_2}\Phi(d_{\beta_2}(P_M^*, F)) \\ +(\beta_1 - 1)\frac{P_M^*Q}{r - \mu}e^{-(r-\mu)T}(1 - \Phi(d_1(P_M^*, F))) \\ +\beta_1\left(\frac{FQ}{r}(1 - e^{-rT}(1 - \Phi(d_0(P_M^*, F)))) - I\right) = 0 \quad \text{for } P_M^* < F \\ \\ (\beta_1 - \beta_2)M_2P_M^{*\beta_2}(1 - \Phi(d_{\beta_2}(P_M^*, F))) \\ +(\beta_1 - 1)\frac{P_M^*Q}{r - \mu}(1 + e^{-(r-\mu)T}(1 - \Phi(d_1(P_M^*, F)))) \\ -\beta_1\left(\frac{FQ}{r}e^{-rT}(1 - \Phi(d_0(P_M^*, F))) + I\right) = 0 \quad \text{for } P_M^* \geq F \end{array} \right. \quad (55)$$

For the case with regulatory uncertainty, Equation (41) results in the following two equations:

$$\left\{ \begin{array}{l} (\eta_1 - \beta_1)(L_1\Phi(d_{\beta_1}) - N_1^{(\omega)})P_{MR}^{*\beta_1} - (\eta_1 - \beta_2)M_2P_{MR}^{*\beta_2}\Phi(d_{\beta_2}) \\ +\eta_1\left(\frac{FQ}{r} - \frac{FQ}{r}e^{-rT}(1 - \Phi(d_0)) - I\right) \\ +(\eta_1 - 1)\frac{P_{MR}^*Q}{r - \mu}e^{-(r-\mu)T}(1 - \Phi(d_1)) = 0 \quad \text{for } P_{MR}^* < F \\ \\ -(\eta_1 - \beta_1)(L_1(1 - \Phi(d_{\beta_1})) + N_1^{(\omega)})P_{MR}^{*\beta_1} + (\eta_1 - \beta_2)M_2P_{MR}^{*\beta_2}(1 - \Phi(d_{\beta_2})) \\ +(\eta_1 - 1)\frac{P_{MR}^*Q}{r - \mu}(1 - e^{-(r-\mu)T}\Phi(d_1)) \\ +e^{-(r-\mu)T} - \eta_1\left(\frac{FQ}{r}e^{-rT}(1 - \Phi(d_0)) + I\right) = 0 \quad \text{for } P_{MR}^* \geq F \end{array} \right. \quad (56)$$

B Proofs of relations between investment thresholds

Proposition 11 *The investment threshold of a project with a finite sliding premium is equal to the investment threshold with a finite minimum price guarantee when the price cap $C \rightarrow +\infty$.*

Proof: We first calculate the limit of the value of the project with a perpetual sliding premium (i.e., Equation (16)) when the price cap $C \rightarrow +\infty$.

As (16) depends on E_1 , G_1 , G_2 , and H_2 , we calculate the limit for each of these variables. In addition, it is easy to see that when $C \rightarrow +\infty$, the third region (i.e, when $P \geq C$) disappears. Hence, we do not calculate the limit of H_2 because it appears only in the third region. Also, recall that G_2 is equal to M_2 .

$$\lim_{C \rightarrow +\infty} E_1 = \frac{F^{1-\beta_1}Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) = L_1 \quad (57)$$

$$\lim_{C \rightarrow +\infty} G_1 = 0 \quad (58)$$

Hence, the value of the project with a perpetual sliding premium when the price cap $C \rightarrow +\infty$ is:

$$V_{CP}(P) = \begin{cases} L_1 P^{\beta_1} + \frac{FQ}{r} & \text{for } P < F \\ M_2 P^{\beta_2} + \frac{PQ}{r - \mu} & \text{for } P \geq F \end{cases} = V_{MP}(P) \quad (59)$$

Therefore, when $C \rightarrow +\infty$, we demonstrate that the value of the project with a perpetual sliding premium is equal to the value of the project with a perpetual minimum price guarantee.

Next, if we let $C \rightarrow +\infty$ in (23) and using the properties of the normal distribution, we conclude the following:

$$\begin{aligned} S_C(P) &= L_1 P^{\beta_1} \Phi(-d_{\beta_1}(P, F)) + \frac{FQ}{r} e^{-rT} \Phi(-d_0(P, F)) \\ &\quad + M_2 P^{\beta_2} \Phi(d_{\beta_2}(P, F)) + \frac{PQ}{r - \mu} e^{-(r-\mu)T} \Phi(d_1(P, F)) = S_M(P) \end{aligned} \quad (60)$$

Hence, when $C \rightarrow +\infty$, 23 is equal to 36. Therefore, the value of the project with a finite sliding premium is equal to the value of the project with a finite minimum price guarantee.

In addition, when $C \rightarrow +\infty$, it is easy to see that the optimal threshold with a finite sliding premium is also equal to the optimal threshold with a finite minimum price guarantee contract for the same sunk cost I .

Proposition 12 *The investment threshold of a project with a finite sliding premium is equal to the investment threshold with a finite fixed price scheme when the price floor F is equal to the price cap C .*

Proof: We first calculate the value of the project with a perpetual sliding premium (i.e., (16)) when the price cap C is equal to the price floor F .

As (16) depends on E_1 , G_1 , G_2 , and H_2 , we first calculate the value of these variables when $C = F$. It is easy to see that E_1 and H_2 are equal to 0, hence the first and third regions (i.e., when $P < F$ and $P \geq C$) are equal $\frac{FQ}{r}$. In addition, substituting F for P and C in the second region also yields to $\frac{FQ}{r}$. Consequently, when $C = F$, $V_{CP}(P) = \frac{FQ}{r}$.

Next, as $\Phi(-d_{\beta}(P, X)) = 1 - \Phi(d_{\beta}(P, X))$, substituting F for P and C in (23) yields:

$$S_C(P) = \frac{FQ}{r} e^{-rT} \quad (61)$$

Therefore, substituting $\frac{FQ}{r} e^{-rT}$ for $S_C(P)$ and $\frac{FQ}{r}$ for $V_{CP}(P)$ in (22) (i.e., the value of the project with a sliding premium) yields:

$$V_C(P) = \frac{FQ}{r} - \frac{FQ}{r} e^{-rT} + \frac{PQ}{r - \mu} e^{-(r-\mu)T} = \frac{FQ}{r} (1 - e^{-rT}) + \frac{PQ}{r - \mu} e^{-(r-\mu)T} \quad (62)$$

In conclusion, the value of the project with a finite sliding premium in (62) (i.e., (22) when $C = F$) is equal to (42) (i.e., the expected value of the project when there is a fixed price scheme). Thus, it is straightforward to see that the investment threshold with a finite sliding premium is equal to the investment threshold when there is a fixed-price scheme.

Proposition 13 *The value of the project with a sliding premium is always smaller than the value of the project with a minimum price guarantee contract.*

Proof: In order to prove the result, we first prove that $V_{MP}(P) \geq V_{CP}(P)$ for any choice of the parameters, i.e., we prove first that the value of the project with a minimum price guarantee contract is always greater than the value of the project with a sliding premium contract, assuming both projects have the same value of the price floor.

We need to distinguish the following cases, depending on the relation between the price P , the minimum price F and the price cap C , as the functions take different forms in each case.

- For $P < F$: in order to prove the result, we just need to prove that $L_1 \geq E_1$. This holds as re-writing E_1 yields:

$$E_1 = \frac{(F^{1-\beta_1} - C^{1-\beta_1})Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) = -\frac{C^{1-\beta_1}Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) + L_1 \quad (63)$$

As $\mu < r$, $\beta_1 > 1$ and $\beta_2 < 0$, it is easy to see that L_1 is greater than E_1 , because $\beta_2\mu - r < 0$. Therefore, when $P < F$, the value of the project with a minimum price guarantee contract is greater than the value of the project with a sliding premium contract.

- For $F \leq P < C$: we prove that $M_2P^{\beta_2} \geq G_1P^{\beta_1} + G_2P^{\beta_2}$.

Re-writing G_1 yields:

$$G_1 = -\frac{C^{1-\beta_1}Q}{\beta_1 - \beta_2} \left(\frac{\beta_2}{r} - \frac{\beta_2 - 1}{r - \mu} \right) < 0 \quad (64)$$

as $\mu < r$, $\beta_1 > 1$ and $\beta_2 < 0$. Therefore the result follows, as $G_2 = M_2$.

- For $P \geq C$: it holds that $M_2P^{\beta_2} + \frac{PQ}{r - \mu} \geq H_2P^{\beta_2} + \frac{CQ}{r}$, as re-writing H_2 yields:

$$H_2 = \frac{(F^{1-\beta_2} - C^{1-\beta_2})Q}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu} \right) = -\frac{C^{1-\beta_2}Q}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu} \right) + M_2 \quad (65)$$

It is easy to see that $\beta_1\mu - r \leq 0$, because of the quadratic equation $\frac{1}{2}\sigma^2\beta(\beta-1) + \beta\mu - r = 0$. As $\beta_1 \geq 1$, the term $\beta_1\mu - r$ is negative. Hence, $H_2 \leq M_2$. In addition, as $P \geq C$ because this is the third branch, it is straight forward to see that $\frac{PQ}{r - \mu} \geq \frac{CQ}{r}$.

It is straight forward to see that the value of the project with a finite minimum price guarantee contract (i.e.: Equation (32)) is also greater than the value of the project with a finite sliding premium contract (i.e.: Equation (22)). In other words, $V_{MP}(P) - S_M(P) + \frac{PQ}{r - \mu}e^{-(r-\mu)T} \geq V_{CP}(P) - S_C(P) + \frac{PQ}{r - \mu}e^{-(r-\mu)T}$, which implies, in its turn, that $S_M(P) \geq S_C(P)$ which, in each case, represents the value of the project with a delayed perpetual feed-in tariff contract. However, the difference between V_M and V_C is greater than the difference between S_M and S_C , because the former also has revenue before time T and the latter only starts to have cash flow after T . In conclusion, the value of the project with a finite minimum price guarantee contract is always greater than the value of the project with a finite sliding premium contract.

C Proofs for the comparative statistics

In this appendix we present the proof of Proposition 10 regarding the comparative statics on the effect of λ and ω grouped by FIT scheme. The proofs are presented briefly, as they follow from long calculations, starting with the simplest cases.

C.1 Fixed-premium FIT

The partial derivatives of the investment threshold is found deriving Equation (52). Let us denote it by E_P .

The partial derivative of P_{PR}^* to a parameter z , given that E_P and P_{PR}^* are both a function of z , is:

$$\frac{\partial P_{PR}^*}{\partial z} = -\frac{\frac{\partial E_P}{\partial z}}{\frac{\partial E_P}{\partial P_{PR}^*}} \quad (66)$$

$$\frac{\partial E_P}{\partial P_{PR}^*} = \left(-\beta_1(\eta_1 - \beta_1)V_1^{(\omega)}P_{PR}^{*\beta_1} + (\eta_1 - 1)\frac{P_{PR}^*Q}{r - \mu} \right) \frac{1}{P_{PR}^*} \quad (67)$$

From the smooth-pasting condition used to obtain Equation (52) we know that

$$\beta_1V_1^{(\omega)}P_{PR}^{*\beta_1} = \frac{P_{PR}^*Q}{r - \mu} - \eta_1W_1P_{PR}^{*\eta_1}, \quad (68)$$

which allows us to obtain:

$$\frac{\partial E_P}{\partial P_{PR}^*} = \left((\eta_1 - \beta_1)\eta_1W_1P_{PR}^{*\eta_1} + (\beta_1 - 1)\frac{P_{PR}^*Q}{r - \mu} \right) \frac{1}{P_{PR}^*} > 0. \quad (69)$$

Since $W_1 > 0$, $\eta_1 > \beta_1 > 1$, this partial derivative is always positive. Therefore, the sign of the partial derivative of the threshold to z is the opposite of the sign of $\frac{\partial E_P}{\partial z}$. It can be shown that these partial derivatives are:

$$\frac{\partial E_P}{\partial \lambda} = -W_1P_{PR}^{*\beta_1}\frac{\partial \eta_1}{\partial \lambda} > 0 \quad (70)$$

$$\begin{aligned} \frac{\partial E_P}{\partial \omega} &= -(\eta_1 - \beta_1)\frac{\partial V_1^{(\omega)}}{\partial \omega}P_{PR}^{*\beta_1} \\ &= -(\eta_1 - \beta_1)\frac{FQ}{r}(1 - e^{-rT})\left(\frac{P_{PR}^*}{P_P^{*(\omega)}}\right)^{\beta_1} < 0 \end{aligned} \quad (71)$$

The signs are obtained knowing that $\frac{\partial \eta_1}{\partial \lambda} < 0$, $\eta_1 > \beta_1 > 1$, $P_{PR}^* \leq P_P^{*(\omega)}$.

C.2 Fixed-price FIT

Similarly to the previous section, the partial derivatives of the investment threshold is found deriving Equation (46). Denoting it by E_F and showing that

$$\frac{\partial E_P}{\partial P_{PR}^*} = \left((\eta_1 - \beta_1)\eta_1U_1P_{PR}^{*\eta_1} + (\beta_1 - 1)\frac{Q}{r - \mu}P_{PR}^* \right) \frac{1}{P_{PR}^*} > 0, \quad (72)$$

the sign of the partial derivative of the threshold to z is the opposite of the sign of $\frac{\partial E_P}{\partial z}$. It can be shown that these partial derivatives are:

$$\frac{\partial E_F}{\partial \lambda} = -U_1P_{FR}^{*\beta_1}\frac{\partial \eta_1}{\partial \lambda} > 0 \quad (73)$$

$$\begin{aligned} \frac{\partial E_F}{\partial \omega} &= -(\eta_1 - \beta_1)\frac{\partial S_1^{(\omega)}}{\partial \omega}P_{FR}^{*\beta_1} \\ &= -(\eta_1 - \beta_1)\frac{FQ}{r}(1 - e^{-rT})\left(\frac{P_{FR}^*}{P_F^{*(\omega)}}\right)^{\beta_1} < 0 \end{aligned} \quad (74)$$

The signs are obtained knowing additionally that $U_1 > 0$, $\frac{\partial \eta_1}{\partial \lambda} < 0$, $\eta_1 > \beta_1 > 1$, $P_{FR}^* \leq P_F^{*(\omega)}$.

C.3 Minimum price guarantee

Similarly to the previous sections, the partial derivatives of the investment threshold is found deriving the two equations in (55). Denoting them by E_M and showing that

$$\frac{\partial E_M}{\partial P_{PR}^*} = \frac{1}{P_{MR}^*} \begin{cases} \eta_1(\eta_1 - \beta_1)R_1P_{MR}^{*\eta_1} - \beta_2(\beta_1 - \beta_2)M_2P_{MR}^{*\beta_2}N(d_{\beta_2}) \\ + (\beta_1 - 1)\frac{P_{MR}^*Q}{r - \mu}e^{-(r-\mu)T}(1 - N(d_1)) > 0 & \text{for } P_{MR}^* < F \\ \eta_1(\eta_1 - \beta_1)R_1P_{MR}^{*\eta_1} \\ - \beta_2((\eta_1 - \beta_1) + (\eta_1 - \beta_2))M_2P_{MR}^{*\beta_2}(N(d_{\beta_2}) - 1) \\ + (\beta_1 - 1)\frac{P_{MR}^*Q}{r - \mu}(1 + e^{-(r-\mu)T}(1 - N(d_1))) > 0 & \text{for } P_{MR}^* \geq F \end{cases} \quad (75)$$

the sign of the partial derivative of the threshold to z is the opposite of the sign of $\frac{\partial E_M}{\partial z}$. It can be shown that these partial derivatives are:

$$\frac{\partial E_M}{\partial \lambda} = -R_1P_{MR}^{*\beta_1}\frac{\partial \eta_1}{\partial \lambda} > 0 \quad (76)$$

$$\begin{aligned} \frac{\partial E_M}{\partial \omega} &= -(\eta_1 - \beta_1)\frac{\partial N_1^{(\omega)}}{\partial \omega}P_{MR}^{*\beta_1} \\ &= -(\eta_1 - \beta_1)\frac{1}{\omega}\left(I - (\beta_1 - 1)N_1^{(\omega)}P_M^{*(\omega)\beta_1}\right)\left(\frac{P_{MR}^*}{P_M^{*(\omega)}}\right)^{\beta_1} < 0 \end{aligned} \quad (77)$$

The signs are obtained knowing that $\frac{\partial \eta_1}{\partial \lambda} < 0$, $\eta_1 > \beta_1 > 1$, $P_{MR}^* \leq P_M^{*(\omega)} \leq P_M^* < P_W^*$, $0 < R_1 \leq N_1^{(\omega)} \leq H_1 < A_{1W}$, and

$$(\beta_1 - 1)N_1^{(\omega)}P_M^{*(\omega)\beta_1} < (\beta_1 - 1)H_1P_M^{*\beta_1} < (\beta_1 - 1)A_{1W}P_M^{*\beta_1} = (\beta_1 - 1)\frac{I}{\beta_1 - 1}\left(\frac{P_M^*}{P_W^*}\right)^{\beta_1} < I.$$

C.4 Sliding premium

The partial derivatives of the investment threshold is found deriving the three Equations that result from (26) and that are presented in Equation (53) in Appendix A.1. Let us denote these equations as E_C .

As for the previous cases, it can be shown that $\frac{\partial E_C}{\partial P_{CR}^*} > 0$. Therefore, the sign of the partial derivative of the threshold to z is the opposite of the sign of $\frac{\partial E_C}{\partial z}$. It can be shown that these partial derivatives are:

$$\frac{\partial E_C}{\partial \lambda} = -K_1P_{MR}^{*\beta_1}\frac{\partial \eta_1}{\partial \lambda} > 0 \quad (78)$$

$$\begin{aligned} \frac{\partial E_C}{\partial \omega} &= -(\eta_1 - \beta_1)\frac{\partial J_1^{(\omega)}}{\partial \omega}P_{MR}^{*\beta_1} \\ &= -(\eta_1 - \beta_1)\frac{1}{\omega}\left(I - (\beta_1 - 1)J_1^{(\omega)}P_C^{*(\omega)\beta_1} + f\right)\left(\frac{P_{CR}^*}{P_C^{*(\omega)}}\right)^{\beta_1} < 0 \end{aligned} \quad (79)$$

where

$$f = \begin{cases} \left((\beta_1 - 1)G_1^{(\omega)}\Phi(d_{\beta_1}(P_C^{*(\omega)}, F)) \right. \\ \quad - (\beta_2 - 1)\left(H_2^{(\omega)} - G_2^{(\omega)}\right)\Phi(d_{\beta_2}(P_C^{*(\omega)}, C)) \\ \quad \left. + \frac{\omega_c C Q}{r}e^{-rT}\Phi(d_0(P_C^*, C)) \right) & \text{for } P_C^{*(\omega)}, F < C \\ \\ \left(-(\beta_1 - 1)G_1^{(\omega)}\left(1 - \Phi(d_{\beta_1}(P_C^{*(\omega)}, F))\right) \right. \\ \quad + (\beta_2 - 1)\left(H_2^{(\omega)} - G_2^{(\omega)}\right)\left(1 - \Phi(d_{\beta_2}(P_C^{*(\omega)}, C))\right) \\ \quad \left. - \frac{\omega_c C Q}{r}\left(1 - e^{-rT}\Phi(d_0(P_C^*, C))\right) \right) & \text{for } P_C^{*(\omega)}, F \geq C \end{cases} \quad (80)$$

The signs are obtained knowing that $\frac{\partial \eta_1}{\partial \lambda} < 0$, $\eta_1 > \beta_1 > 1$, $P_{CR}^* \leq P_C^{*(\omega)}$, and

$$I - (\beta_1 - 1)J_1^{(\omega)}P_C^{*(\omega)\beta_1} + f > 0.$$

The sign of this equation is proved by deriving the value of option to invest in a sliding-premium FIT without the floor (a cap FIT), denoted by $Z_1^{(\omega)}P_1^\beta$ (for instance taking C to the limit of 0). It can be shown that $f > (\beta_1 - 1)Z_1^{(\omega)}P_C^{*(\omega)\beta_1} - I$ and $Z_1^{(\omega)} > J_1^{(\omega)}$.

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