Analysis of Renewable Energy Policy: Feed-in Tariffs with Minimum Price Guarantees

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Abstract

Policy intervention can impact the decision making process of deploying a renewable energy project. The feed-in tariff (FIT) program is a popular policy for incentivizing new renewable energy projects, because it establishes a long-term contract with renewable energy producers. This paper presents a model to analyze a FIT contract with a minimum price guarantee in two distinct scenarios. First, we analyze FIT contracts in an oligopolistic market structure. The derivation uses an asymmetric Stackelberg model with a real options valuation model. Second, we analyze a price-taker scenario with a real options valuation model. We also analyze the FIT contracts with a perpetual and finite duration in both scenarios. With the model, we can find several interesting properties. For example, we can first identify the optimal time to deploy a renewable energy project. Second, we can analyze how the value and duration of a minimum price guarantee affects the investment threshold and the value of the project. The results show that a perpetual guarantee can induce investment for prices below the minimum price guarantee, when the project compensates the investment cost. Another interesting result is that a FIT contract with a higher price and duration induces an earlier investment. From a managerial perspective, our model provides a powerful tool to analyze investment in renewable energy projects where we take into account managerial flexibilities and a FIT policy with a minimum price guarantee.

JEL Classification: L94, Q42, C72
Keywords: Asymmetric Stackelberg Equilibrium, Perpetual guarantee, Finite guarantee, Feed-in tariff

1 Introduction

The generation of energy from renewable resources, such as wind and sunlight, is an important option that can mitigate many environmental problems. In addition, the utilization of depletable resources, such as gas or coal, for generating energy is a problem from a sustainability perspective, since supplies used now are not available for future generations. Therefore, policymakers must incentivize energy generation through renewable resource, and consequently decrease the cost of scarcity for society and price of resources, and increase the social welfare.

There are many policies to incentivize renewable energy projects (Grubb 2004), which in turn might reduce environmental pollution, global warming and public health issues. For instance, the Renewable Portfolio Standards (Wiser, Namovicz, Gielecki & Smith 2007) in the US and the RES Directive (Klessmann, Lamers, Ragwitz & Resch 2010) in the EU are policies that are playing an increasingly important role in the decision-making process of generation companies.

Policy intervention can have a significant impact on the decision of deploying a renewable energy project. Couture & Gagnon (2010) state that the feed-in tariff (FIT) program is considered one of the most important policies for stimulating new renewable energy projects. FIT program is a long-term contract with renewable energy producers (e.g., homeowners, business and organizations such as schools and community groups) to enhance energy generation. In addition, Couture & Gagnon (2010) present many different remuneration schemes utilized by policymakers that have evolved over time.

This article presents a model to analyze a FIT policy with a minimum price guarantee in two scenarios, namely an oligopoly and a price-taker scenario. The model includes managerial flexibilities and identifies the optimal timing for the investment in a renewable energy project. The model also takes into account the effect of the duration of the guarantee: hence, we analyze a perpetual and finite guarantee.

In particular, the oligopolistic market structure uses an asymmetric Stackelberg model with a real options valuation model. The price-taker scenario uses a real options valuation model. In both scenarios, the renewable energy producer receives either the energy market price or a minimum price guarantee. We use the model to analyze how the value and duration of a minimum price guarantee affects the investment threshold and the value of the project.

The results show that a perpetual guarantee can induce investment for prices below the minimum price, when the project compensates the investment cost.

This paper is organized as follows. Section 2 presents the related work and our main contributions to literature. Section 3 analyzes a minimum price guarantee FIT within an oligopoly. Section 4 presents a FIT analysis with many renewable energy producers that are Price taker. Finally, Section 5 presents the concluding remarks.

2 Related Work

In literature, many papers have used the Cournot or Stackelberg game to model energy markets in order to predict interesting economic results. In fact, Cournot oligopolies are very popular because the majority of electricity markets nowadays are neither a monopoly nor a perfect competition; Twomey & Neuhoff (2010) state that modeling the market as an oligopoly is the most appropriate assumption. Moreover, these analyses can lead to policies that may resolve some of the economic and sustainability issues.

For instance, Wolfram (1999) analyzes the market power of generation companies in the British electricity market, and shows that prices are lower than estimates due to many reasons, such as entry deterrence and actions from the regulator. Chuang, Wu & Varaiya (2001) formulate a Cournot oligopoly market for generation expansion planning, and present numerical results to analyze industry expansion, generation investment and trends. Murphy & Smeers (2005) present an open-loop and closed-loop Cournot model, in which investment and power dispatch decisions occur simultaneously in the former model and in two stages in the latter model; in addition, this work compares both models with a perfect competition. Nanduri, Das & Rocha (2009) utilize a similar single stage Cournot model as Murphy & Smeers (2005) taking into consideration the network transmission constraints. Chang, Hu & Han (2013) use a Stackelberg game to analyze a constant price FIT contract in Taiwan. Twomey & Neuhoff (2010) examine the case of intermittent generation return under perfect competition, monopoly and oligopoly; the results show that, when different technologies are used, the market participants benefit differently from the increased price. Moreover, intermittent technologies benefit less from the market power effect than conventional technologies.

However, despite the numerous of papers with oligopolies for energy markets, not much has been said (if any) about the impact of the duration of a guarantee, namely a minimum price guarantee, and the effect of managerial flexibilities. Moreover, although our model focus on the minimum price guarantee, it can be easily extend to a market dependent Feed in tariff where the firm receives a bonus over the market price.

Our model relates and contributes to the literature in several ways. Our first contribution is to game theory, where we extend the Stackelberg model in order to value managerial flexibilities and identify the optimal timing for the investment in a renewable energy project. The model also takes into account the effect of minimum price guarantee FIT policies, using the Shackleton & Wojakowski (2007) framework. In particular, we show how the value and duration of a FIT change the investment threshold.

Our second contribution is to real option community, where we extend Shackleton & Wojakowski (2007) and develop two models: the first one with a perpetual guarantee and the second with a finite guarantee. The model shows that perpetual guarantee can only induce investment for prices below the FIT if it at least compensates the investment sunk cost.

Our third contribution is to energy research community, where we present a powerful model taking into account a FIT policy and managerial flexibilities within an oligopoly market. We show how a FIT may affect the investment decision in renewable energy projects.

3 Oligopolistic Market Structure and FIT Policy

The majority of electricity markets nowadays are neither a monopoly nor a perfect competition. In fact, Twomey & Neuhoff (2010) state that modeling the market as an oligopoly is the most appropriate assumption. We thus analyze a minimum price guarantee FIT within an oligopolistic market.

The model has a conventional energy producer that acts as the leader and the follower is a renewable energy producer. Hence, we analyze the producers within a Stackelberg game. We then include managerial flexibilities with a real option model. We start assuming that the producers face the linear inverse demand function of the following form:

$$P(Q,t) = ax(t) - bQ_T(t) \tag{1}$$

where $a > 0$ represents the market size, $b > 0$ shows how price changes affect the demand function, $x(t)$ denotes the industry's demand shock at time t observed by all firms, and $Q_T(t)$ is the total output produced. We assume that the industry's demand shock follows the geometric Brownian motion process.

$$dx_t = \mu x_t dt + \sigma x_t dW_t \tag{2}$$

where $\mu < r$ is a deterministic drift, $\sigma > 0$ is the volatility, and dW_t is the standard Brownian motion process. The volatility σ can be estimated (e.g., through OLS) from the returns of the historical data.

We denote the conventional energy producer with a subscript c and the renewable energy producer with a subscript r. The profit function of the conventional energy producer is:

$$\Pi_c = P(Q_T)q_c - c_c \tag{3}$$

where q_c is the quantity produced. The cost function has the following form $c_c = q_c^2/2k_c$, where k_c is the conventional energy producer's capacity.

The profit function of the renewable energy producer is:

$$\Pi_r = Max(F, P(Q_T))q_r - c_r \tag{4}$$

where, F is a minimum price guarantee due to a FIT contract. The cost function also has the following form $c_r = q_r^2/2k_r$ where k_r is the renewable energy producer's capacity.

The production cost of conventional energy is different from the renewable energy. For instance, the production cost of wind power is almost zero (Twomey & Neuhoff 2010). This rationale leads to a different cost function for each producer, as described above.

In the Stackelberg game, the market equilibrium is:

$$q_c = \frac{ak_c(bk_r + 1)}{2b(bk_r k_c + k_r + k_c) + 1}x \tag{5}$$

If the renewable energy producer receives the market price, the profit is:

$$\Pi_r = \frac{a^2 k_r(b(k_r(bk_c + 2) + k_c) + 1)^2}{2(2bk_r + 1)(2b(bk_r k_c + k_r + k_c) + 1)^2}x^2 = \alpha x^2 \tag{6}$$

When the market price is below the minimum price guarantee, the energy production yields a different profit due to the FIT contract:

$$\Pi_r = \frac{F^2 k_r}{2} \tag{7}$$

Note that the profit function in Equation 6 is proportional to x^2, hence, it is straightforward to prove by Itô's Lemma that the profit follows the following stochastic process:

$$d\Pi = (2\mu + \sigma^2)\Pi_t dt + 2\sigma\Pi_t dW_t \tag{8}$$

Hence, the appropriate discounted rate to find the value of the project when the market price, p, is greater than the minimum price guarantee, F, is:

$$R = r - 2\mu - \sigma^2 \tag{9}$$

The renewable energy producer maximizes its profit by choosing an appropriate quantity that depends on x. However, the producer with a FIT contract receives a fixed amount when the market price is below the minimum price guarantee. Let us denote x_F as the point where the profit received by the equilibrium market price (Equation 6) is equals to the profit received by FIT contract (Equation 7). Hence,

$$x_F = F\sqrt{\frac{k_r}{2\alpha}} \tag{10}$$

3.1 Perpetual FIT within an Oligopoly

In this section, we assume that the duration of the FIT contract is perpetual. Hence, the renewable energy producer has a perpetual set of options of selling energy for F instead of selling energy for the market price p. For any value of x at any time t, the option is exercised when the profit generated by F is greater than the profit generated by p. This characteristic is consistent with European put options and not an American options, because each option can only be exercised at its specified instant. In contrast, an American option can be exercised at any time before maturity.

Let $V(x)$ be the value of the project. Therefore the differential equation for the value of the project is:

$$rV = \alpha\, x\frac{\partial V(x)}{\partial x} + 0.5\sigma^2\, x^2\,\frac{\partial^2 V(x)}{\partial x^2} + \Pi(x) \tag{11}$$

where

$$\Pi(x) = \begin{cases} \dfrac{F^2 k_r}{2r} & x < x_F \\ \\ \dfrac{\alpha x^2}{R} & x > x_F \end{cases} \tag{12}$$

And the general solution to this ODE is given by:

$$V(x) = Kx^{\beta_1} + Bx^{\beta_2} \tag{13}$$

Following Dixit & Pindyck (1994), the value of the project is:

$$V(x) = \begin{cases} Kx^{\beta_1} + \dfrac{F^2 k_r}{2r} & x < x_F \\ \\ Bx^{\beta_2} + \dfrac{\alpha x^2}{R} & x > x_F \end{cases} \tag{14}$$

where

$$K = \frac{\dfrac{\beta_2 F^2 k_r}{2r} - \dfrac{(\beta_2 - 2)(\alpha x_F^2)}{R}}{(\beta_1 - \beta_2) x_F^{\beta_1}} \tag{15}$$

$$B = \frac{\dfrac{\beta_1 F^2 k_r}{2r} - \dfrac{(\beta_1 - 2)(\alpha x_F^2)}{R}}{(\beta_1 - \beta_2) x_F^{\beta_2}} \tag{16}$$

Let us assume now that the firm has a perpetual option to invest, for a given sunk cost I. The value of that option is given by:

$$F(x) = Ax^{\beta_1} \tag{17}$$

For $x > x_F$, the value matching and smooth pasting conditions are:

$$Ax^{*^{\beta_1}} = Bx^{*^{\beta_2}} + \frac{\alpha}{R} x^{*^2} - I \tag{18}$$

$$\beta_1 A x^{*^{\beta_1 - 1}} = B\beta_2 x^{*^{\beta_2 - 1}} + \frac{2\alpha}{R} x^* \tag{19}$$

where x^* is the threshold for investment.

These two equations reduce to the following non-linear equation:

$$(1 - \beta_2) Bx^{*^{\beta_2}} - \frac{\alpha}{R} x^{*^2} - I = 0 \tag{20}$$

We can calculate the trigger for investment, x^*, by numerically solving Equation 20. It is straightforward to show that investment will never occur for $x < x_F$. Value matching and smooth pasting conditions are not met for the the first branch of Equation 14. A perpetual FIT will defer investment until a time when the state variable x is higher than x_F, meaning that it is never optimal to invest if the initial price for selling energy is below the minimum price guarantee. This apparently counter-intuitive result is due to the perpetual guarantee, which is not foregone if investment does not occur. The next section studies the case of a finite-lived guarantee.

3.2 Finite FIT within an Oligopoly

In this section, we derive the value of a renewable energy project that has a FIT contract with a finite duration. The complete derivation is presented in Appendix A, where we extend the model from Shackleton & Wojakowski (2007) to include an equilibrium analysis and FIT policy.

Equation 21 presents the value of the project until T (when the firm benefits from the FIT guarantee) and Equation 23 presents the value of the project with a finite FIT contract.

$$V^G(x) = \begin{cases} Kx^{\beta_1} N(d_{\beta_1}) + \dfrac{F^2 k_r}{2r}\left(1 - e^{-rT}(1 - N(d_0))\right) \\ \quad -Bx^{\beta_2} N(d_{\beta_2}) - \dfrac{\alpha x^2}{R} e^{-RT} N(d_2) & x < x_F \\ \\ -Kx^{\beta_1}(1 - N(d_{\beta_1})) - \dfrac{F^2 k_r}{2r} e^{-rT}(1 - N(d_0)) \\ \quad +Bx^{\beta_2}(1 - N(d_{\beta_2})) + \dfrac{\alpha x^2}{R}\left(1 - e^{-RT} N(d_2)\right) & x > x_F \end{cases} \tag{21}$$

where $N(.)$ is the cumulative normal integral and

$$d_\beta = \frac{\ln \dfrac{x}{x_F} + \left(\mu + \sigma^2\left(\beta - \dfrac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \tag{22}$$

$$V(x) = V^G(x) + \frac{\alpha x^2}{R} e^{-RT} \tag{23}$$

When there is no guarantee ($T = 0$) the value of the project reduces to $\frac{\alpha x}{R}$, which is the present value of the profits in Equation 6. When the guarantee is perpetual ($T = \infty$), the value reduces to Equation 14.[1]

The value of the option to invest is:

$$F(x) = Ax^{\beta_1} \tag{24}$$

The value matching and smooth pasting conditions are:

$$Ax^{*\beta_1} = V(x^*) - I \tag{25}$$

$$\beta_1 A x^{*\beta_1 - 1} = V'(x^*) \tag{26}$$

[1] Proofs are presented in Appendix B.

These two equations reduce to the following nonlinear equations, that must be solved numerically to find the investment threshold x^* (Appendix C):

$$\begin{cases} -(\beta_1-\beta_2)Bx^{*\beta_2}N(d_{\beta_2}) - (\beta_1-2)\left(\frac{\alpha x^{*2}}{R}e^{-RT}N(d_2)\right) \\ \quad +\beta_1\left(\frac{F^2k_r}{2r}(1-e^{-rT}(1-N(d_0))) - I\right) & x^* < x_F \\ \\ (\beta_1-\beta_2)Bx^{*\beta_2}(1-N(d_{\beta_2})) + (\beta_1-2)\left(\frac{\alpha x^{*2}}{R}(1-e^{-RT}N(d_2))\right) \\ \quad -\beta_1\left(\frac{F^2k_r}{2r}e^{-rT}(1-N(d_0)) + I\right) & x^* > x_F \end{cases} \tag{27}$$

The value of the option to invest is given by:

$$F(x) = \begin{cases} (V(x^*) - I)\left(\frac{x}{x^*}\right)^{\beta_1} & x < x^* \\ \\ V(x) - I & x > x^* \end{cases} \tag{28}$$

3.3 Numerical analysis of the FIT Policy within an Oligopoly

In this section we present a comparative statics analysis of the main drivers of a renewable energy producer's option to invest and its threshold. We use the base-case parameters presented in Table 1.

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

a	10
b	0.1
kl	1
kf	0.2
r	0.05
F	€1 / KWh
T	5 years
μ	-0.01
σ	0.2
I	€10

Figure 1 illustrates the value of the threshold x^* for a finite guarantee (pink curve) and for a perpetual guarantee (blue curve) as a function of the minimum price guarantee F. The gray line is the value of x_F as a function of F. Recall that x_F is the value of x when the producer receives the market price instead of the guarantee.

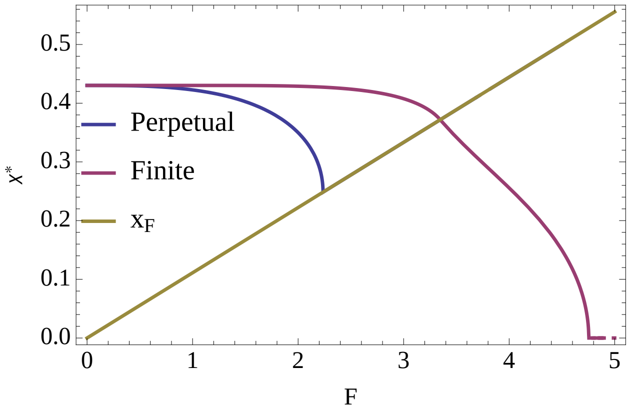

Figure 1: Investment thresholds as a function of the minimum price guarantee

For the perpetual case, the threshold reduces and converges to x_F from above as we increase F. At the point where the two lines converge, the perpetual guarantee produces a positive net present value (NPV) for every x and a null NPV for $x = 0$. Hence, a perpetual FIT is sufficient to induce investment for every x. However, it is not economically sound to increase the FIT guarantee above the point where the two lines converge, as it will produce always a risk-free profit. On the contrary, a finite FIT guarantee is able to induce investment below x_F without producing a risk-free profit. For the base-case parameter, a minimum price guarantee around 4.8 is the maximum needed to induce investment for every x. As expected, the investment threshold is higher for the finite case.

Figure 2 shows that a higher duration of the guarantee induces an earlier investment. The threshold also converges to the perpetual case as T increases. In Figure 3, we can see that a higher volatility defers investment for both cases.

4 Price Taker Scenario and FIT Policy

In this section, the scenario has a large number of renewable energy producers with small scale projects. A renewable energy producer is not influential enough to affect the market price. In other words, the renewable energy

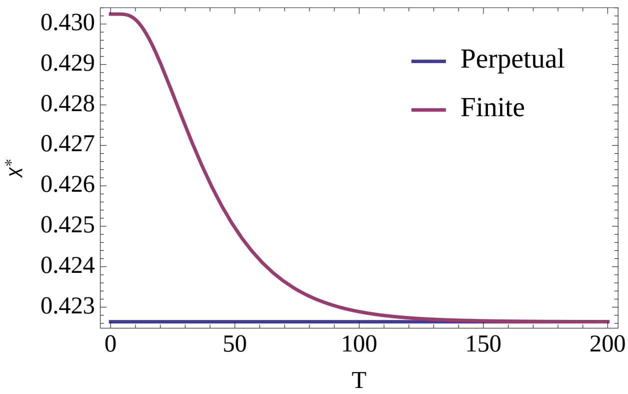

Figure 2: Investment thresholds as a function of T

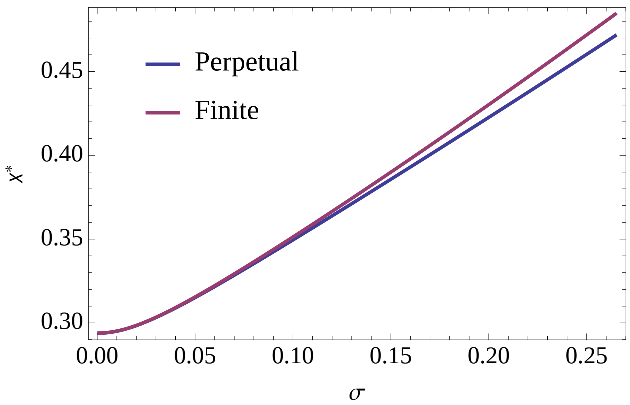

Figure 3: Investment thresholds as a function of σ

producers are Price taker. The energy price follows a geometric Brownian process, which is the usual assumption in real options models.

$$dp_t = \mu p_t dt + \sigma p_t dW_t \tag{29}$$

4.1 Perpetual FIT within the Price Taker Scenario

We first present a model that assumes a FIT contract with a perpetual duration. In this scenario, the value of the project is:

$$V(p) = \begin{cases} Kp^{\beta_1} + \dfrac{F}{r} & p < F \\ \\ Bp^{\beta_2} + \dfrac{p}{r-\mu} & p > F \end{cases} \tag{30}$$

The two regions above meet when $p = F$. Recall that $V(p)$ must be continuously differentiable across F. Equating the values and derivatives gives:

$$K = \frac{\dfrac{F\beta_2}{r} - \dfrac{F(\beta_2 - 1)}{r - \mu}}{F^{\beta_1}(\beta_1 - \beta_2)} \tag{31}$$

$$B = \frac{\dfrac{F\beta_1}{r} - \dfrac{F(\beta_1 - 1)}{r - \mu}}{F^{\beta_2}(\beta_1 - \beta_2)} \tag{32}$$

Following the assumption that a firm has a perpetual option to invest, for a sunk cost of I, will lead to a value of the option that is given by:

$$F(x) = Ax^{\beta_1} \tag{33}$$

The value matching and smooth pasting conditions for $p > F$ are:

$$Ap^{*^{\beta_1}} = Bp^{*^{\beta_2}} + \frac{p^*}{r - \mu} - I \tag{34}$$

$$A\beta_1 p^{*^{\beta_1 - 1}} = B\beta_2 p^{*^{\beta_2 - 1}} + \frac{1}{r - \mu} \tag{35}$$

The two equations reduce to the following non-linear equation:

$$(\beta_1 - \beta_2)Bp^{*^{\beta_2}} + (\beta_1 - 1)\frac{p^*}{r - \mu} - I\beta_1 = 0 \tag{36}$$

The trigger for investment, p^* is the numerical solution to Equation 36. It is straightforward to show that the results are the same as in the Oligopoly scenario. Hence, a perpetual FIT defers investment until a time when the state variable p is higher than F. This means that it is never optimal to invest if the price at which the firm will start selling energy is bellow the minimum price guarantee. The next section studies the case of a FIT with a finite guarantee, assuming producers are Price taker.

4.2 Finite FIT within the Price Taker Scenario

Similar to the previous section, we use Shackleton & Wojakowski (2007) to derive the value of the project for a FIT contract with a finite duration. The complete derivation is presented in Appendix D.

Equation 37 presents the value of the project until T, when the firm benefits from the FIT guarantee. Equation 39 presents the value of the project with a finite FIT contract.

$$V^G(p) = \begin{cases} Kp^{\beta_1}N(d_{\beta_1}) + \dfrac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ \qquad -Bp^{\beta_2}N(d_{\beta_2}) - \dfrac{p}{r-\mu}e^{-(r-\mu)T}N(d_1) & p < F \\ \\ -Kp^{\beta_1}(1 - N(d_{\beta_1})) - \dfrac{F}{r}e^{-rT}(1 - N(d_0)) \\ \qquad +Bp^{\beta_2}(1 - N(d_{\beta_2})) + \dfrac{p}{r-\mu}(1 - e^{-(r-\mu)T}N(d_1)) & p > F \end{cases} \tag{37}$$

where $N(.)$ is the cumulative normal integral and

$$d_\beta = \frac{\ln\dfrac{p}{F} + \left(\mu + \sigma^2\left(\beta - \dfrac{1}{2}\right)\right)T}{\sigma\sqrt{T}} \tag{38}$$

$$V(p) = V^G(p) + \frac{p}{r-\mu}e^{-(r-\mu)T} \tag{39}$$

When there is no guarantee (i.e., $T = 0$) the value of the project reduces to the present value $\frac{p}{r-\mu}$. In the case of a perpetual guarantee (i.e., $T = \infty$), the value reduces to Equation 30.[2]

The value of the option to invest is:

$$F(p) = Ap^{\beta_1} \tag{40}$$

The value matching and smooth pasting conditions are:

$$Ap^{*\beta_1} = V(p^*) - I \tag{41}$$

$$\beta_1 Ap^{*\beta_1 - 1} = V'(p^*) \tag{42}$$

These two equations reduce to the following nonlinear equations, that must be solved numerically to find the investment threshold p^* (Appendix

[2]Proofs are presented in Appendix E.

F):

$$
\begin{cases}
-(\beta_1-\beta_2)Bp^{*\beta_2}N(d_{\beta_2})-(\beta_1-1)\left(\dfrac{p^*}{r-\mu}e^{-(r-\mu)T}N(d_1)\right) & \\
\qquad +\beta_1\left(\dfrac{F}{r}(1-e^{-rT}(1-N(d_0)))-I\right) & p^*<F \\
 & \\
(\beta_1-\beta_2)Bp^{*\beta_2}(1-N(d_{\beta_2}))+(\beta_1-1)\left(\dfrac{p^*}{r-\mu}(1-e^{-(r-\mu)T}N(d_1))\right) & \\
\qquad -\beta_1\left(\dfrac{F}{r}e^{-rT}(1-N(d_0))+I\right) & p^*>F
\end{cases}
\tag{43}
$$

The value of the option to invest is given by:

$$
F(p)=\begin{cases}
(V(p^*)-I)\left(\dfrac{p}{p^*}\right)^{\beta_1} & p<p^* \\
 & \\
V(p)-I & p>p^*
\end{cases}
\tag{44}
$$

4.3 Numerical analysis within the Price Taker Scenario

Similar to the previous section, we present çmparative statics to analyze the option to invest and the threshold that triggers a renewable energy investment. We use the base-case parameters presented in Table 2.

Table 2: Base-case parameters used to calculate the threshold

r	0.05
F	€1 / KWh
T	5 years
μ	-0.01
σ	0.2
I	€30

Figure 4 presents the value of the threshold p^* for a finite guarantee (pink curve) and for a perpetual guarantee (blue curve) as a function of the minimum price guarantee F. The gray line is the value of the minimum price guarantee F.

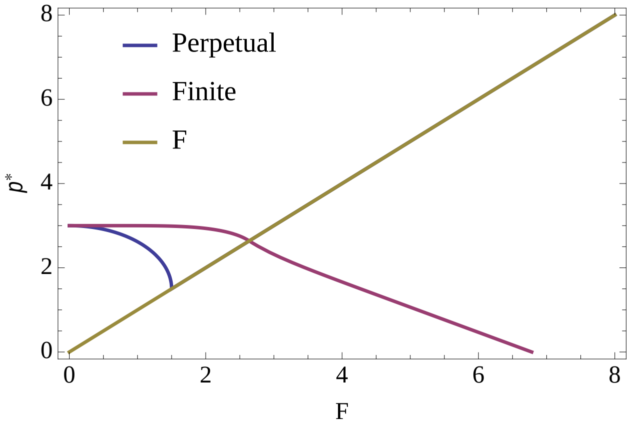

Figure 4: Investment thresholds as a function of the FIT

Similar to the oligopoly scenario, the threshold of the perpetual case starts above F and then converges to F. Notice that the perpetual guarantee produces a positive NPV when the two lines converge. Hence, increasing the minimum price guarantee above that point is not economically sound, because it will produce always a risk-free profit. A finite FIT guarantee is able to induce investment below F without producing a risk-free profit. Considering the base-case parameter of Table 2, a minimum price guarantee around 6.8 is the maximum needed to induce investment for every p. As expected, the investment threshold is higher for the finite case.

A higher duration of the guarantee induces an earlier investment, and the threshold converges to the perpetual case (Figure 5). A higher volatility defers investment for both cases (Figure 6).

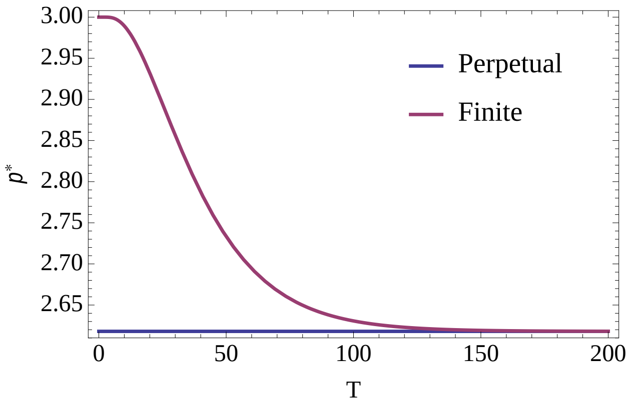

Figure 5: Investment thresholds as a function of T

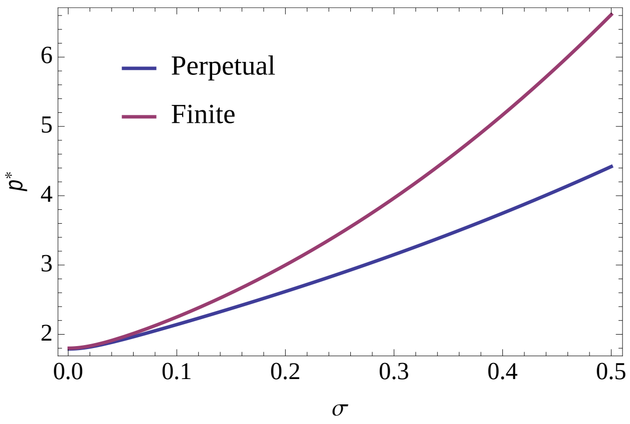

Figure 6: Investment thresholds as a function of σ

5 Concluding Remarks

This work analyzes a FIT contract with a minimum price guarantee in two different scenarios, namely an oligopoly and price-taker scenario. In the oligopoly, we use a Stackelberg game and include managerial flexibilities with a real options model. While the price-taker scenario is based on a real options model. In both scenarios, the renewable energy producer receives either the energy market price or a minimum price guarantee. The key results of this paper is twofold. First, both scenarios show that a perpetual guarantee can induce investment for prices below the minimum price guarantee, when the project compensates the investment cost. Second, FIT contracts with a higher price and duration induces an earlier investment.

Appendix A Value of the project for a finite FIT

This is an extension of Shackleton & Wojakowski (2007) to a renewable energy project, where we include a FIT and an equilibrium analysis. The value of the project with perpetual guarantee is:

$$V(x_T, \infty) = \begin{cases} Kx^{\beta_1} + \dfrac{F^2 k_r}{2r} & x_T < x_F \\ \\ Bx^{\beta_2} + \dfrac{\alpha x^2}{R} & x_T > x_F \end{cases} \tag{A.1}$$

Now, the value of the project is extended with finite guarantee. For more details see Appendix A of Shackleton & Wojakowski (2007).

$$V(x,T) = V(x,\infty) - V(x_T,\infty) = V(x,\infty) - e^{-rT} E_0^Q[V(x_T,\infty)] \tag{A.2}$$

$$V(x,\infty) = \left[Kx^{\beta_1} + \frac{F^2 k_r}{2r}\right] 1_{x<x_F} + \left[Bx^{\beta_2} + \frac{\alpha x^2}{r - 2\mu - \sigma^2}\right] 1_{x>x_F} \tag{A.3}$$

$$V(x_T,\infty) = \left[Kx_T^{\beta_1} + \frac{F^2 k_r}{2r}\right] 1_{x_T<x_F} + \left[Bx_T^{\beta_2} + \frac{\alpha x_T^2}{r - 2\mu - \sigma^2}\right] 1_{x_T>x_F} \tag{A.4}$$

$$d_\beta = \frac{\ln \dfrac{x}{x_F} + \left(\mu + \sigma^2\left(\beta - \dfrac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \tag{A.5}$$

$$q(\beta) = \frac{1}{2}\sigma^2 \beta(\beta - 1) + \beta\mu - r \tag{A.6}$$

$$e^{-rT} E_0^Q \left[x_T^\beta 1_{x_T<x_F}\right] = e^{q(\beta)T} x^\beta N(-d_\beta) \tag{A.7}$$

$$e^{-rT} E_0^Q \left[x_T^\beta 1_{x_T>x_F}\right] = e^{q(\beta)T} x^\beta N(d_\beta) \tag{A.8}$$

$$
\begin{aligned}
\beta &= \beta_1 \\
q(\beta_1) &= 0 \\
d_{\beta_1} &= \frac{\ln \dfrac{x}{x_F} + \left(\mu + \sigma^2 \left(\beta_1 - \dfrac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \\
e^{-rT} E_0^Q \left[K x^{\beta_1}\right] &= K x^{\beta_1} N(-d_{\beta_1})
\end{aligned}
\tag{A.9}
$$

$$
\begin{aligned}
\beta &= 0 \\
q(0) &= -r \\
d_0 &= \frac{\ln \dfrac{x}{x_F} \left(\mu - \dfrac{\sigma^2}{2}\right) T}{\sigma\sqrt{T}} \\
e^{-rT} E_0^Q \left[\frac{F^2 k_r}{2r}\right] &= e^{-rT} \frac{F^2 k_r}{2r} N(-d_0)
\end{aligned}
\tag{A.10}
$$

$$
\begin{aligned}
\beta &= \beta_2 \\
q(\beta_2) &= 0 \\
d_{\beta_2} &= \frac{\ln \dfrac{x}{x_F} \left(\mu + \sigma^2 \left(\beta_2 - \dfrac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \\
e^{-rT} E_0^Q \left[B x^{\beta_2}\right] &= B x^{\beta_2} N(d_{\beta_2})
\end{aligned}
\tag{A.11}
$$

$$
\begin{aligned}
\beta &= 2 \\
q(2) &= \sigma^2 + 2\mu - r \\
d_2 &= \frac{\ln \frac{x}{x_F} + \left(\mu + \frac{3\sigma^2}{2}\right) T}{\sigma\sqrt{T}} \\
e^{-rT} E_0^Q \left[\frac{\alpha x^2}{R}\right] &= \frac{\alpha x^2}{R} N(d_2) e^{-RT}
\end{aligned}
\tag{A.12}
$$

Recall that $V(x, T) = V(x, \infty) - e^{-rT} E_0^Q[V(x_T, \infty)]$

For $x < x_F$

$$
\begin{aligned}
&Kx^{\beta_1} + \frac{F^2 k_r}{2r} \\
&- \left[Kx^{\beta_1} N(-d_{\beta_1}) + \frac{F^2 k_r}{2r} e^{-rT} N(-d_0) + Bx^{\beta_2} N(d_{\beta_2}) + \frac{\alpha x^2}{R} e^{-RT} N(d_2)\right]
\end{aligned}
\tag{A.13}
$$

$N(-d_\beta) = 1 - N(d_\beta)$. Hence, for $x < x_F$

$$
Kx^{\beta_1} N(d_{\beta_1}) + \frac{F^2 k_r}{2r} \left(1 - e^{-rT}(1 - N(d_0))\right) - Bx^{\beta_2} N(d_{\beta_2}) - \frac{\alpha x^2}{R} e^{-RT} N(d_2) \tag{A.14}
$$

For $x > x_F$

$$
\begin{aligned}
&Bx^{\beta_2} + \frac{\alpha x^2}{R} \\
&- \left[Kx^{\beta_1} N(-d_{\beta_1}) + \frac{F^2 k_r}{2r} e^{-rT} N(-d_0) + Bx^{\beta_2} N(d_{\beta_2}) + \frac{\alpha x^2}{R} e^{-RT} N(d_2)\right]
\end{aligned}
\tag{A.15}
$$

$$
- Kx^{\beta_1}(1-N(d_{\beta_1})) - \frac{F^2 k_r}{2r} e^{-rT}(1-N(d_0)) \\
+ Bx^{\beta_2}(1-N(d_{\beta_2})) + \frac{\alpha x^2}{R}\left(1 - e^{-RT}N(d_2)\right) \quad \text{(A.16)}
$$

$$
V^G(x) = \begin{cases} Kx^{\beta_1}N(d_{\beta_1}) + \frac{F^2 k_r}{2r}\left(1 - e^{-rT}(1-N(d_0))\right) & \\ \quad -Bx^{\beta_2}N(d_{\beta_2}) - \frac{\alpha x^2}{R}e^{-RT}N(d_2) & x < x_F \\ & \\ -Kx^{\beta_1}(1-N(d_{\beta_1})) - \frac{F^2 k_r}{2r}e^{-rT}(1-N(d_0)) & \\ \quad +Bx^{\beta_2}(1-N(d_{\beta_2})) + \frac{\alpha x^2}{R}\left(1 - e^{-RT}N(d_2)\right) & x > x_F \end{cases} \quad \text{(A.17)}
$$

Now, we add the part without guarantee

$$
V(x) = V^G(x) + \frac{\alpha x^2}{R}e^{-RT} \quad \text{(A.18)}
$$

Appendix B Limits of the value of project for a finite FIT

Checking the limit for $T \to +\infty$

$$\lim_{T\to+\infty} d_0 = \lim_{T\to+\infty} \frac{\ln\frac{x}{x_F} + \left(\mu - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = \begin{cases} -\infty & \mu - \frac{\sigma^2}{2} < 0 \\ \\ +\infty & \mu - \frac{\sigma^2}{2} > 0 \end{cases} \tag{B.1}$$

$$\lim_{T\to+\infty} d_2 = \lim_{T\to+\infty} \frac{\ln\frac{x}{x_F} + \left(\mu + \frac{3\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = +\infty \tag{B.2}$$

$$\lim_{T\to+\infty} d_{\beta_1} = \lim_{T\to+\infty} \frac{\ln\frac{x}{x_F} + \left(\mu + \sigma^2\left(\beta_1 - \frac{1}{2}\right)\right)T}{\sigma\sqrt{T}} = +\infty \tag{B.3}$$

$$\lim_{T\to+\infty} d_{\beta_2} = \lim_{T\to+\infty} \frac{\ln\frac{x}{x_F} + \left((\mu + \sigma^2\left((\beta_2 - \frac{1}{2}\right)\right)T}{\sigma\sqrt{T}} = -\infty \tag{B.4}$$

Recall that $\beta_2 < 0$ and $\beta_1 > 1$. In addition, β_1 and β_2 is the solution of the following quadratic equation: $0.5\sigma^2\beta(\beta-1)+\mu\beta-r$. Hence $\lim_{T\to+\infty} d_{\beta_2}$ is always $-\infty$.

$$0.5\sigma^2\beta(\beta - 1) + \mu\beta - r = 0 \tag{B.5}$$

$$\mu = \frac{r - 0.5\sigma^2\beta_2(\beta_2 - 1)}{\beta_2} \tag{B.6}$$

$$\mu + \sigma^2(\beta_2 - 0.5) = \frac{r - 0.5\sigma^2\beta_2(\beta_2 - 1)}{\beta_2} + \sigma^2(\beta_2 - 0.5) \tag{B.7}$$

$$\mu + \sigma^2(\beta_2 - 0.5) = \frac{r + 0.5\sigma^2\beta_2^2}{\beta_2} < 0 \tag{B.8}$$

$$N(+\infty) = 1 \tag{B.9}$$

$$N(-\infty) = 0 \tag{B.10}$$

$\lim_{T\to+\infty}$ for $x < x_F$

$$\lim_{T\to+\infty}\Big[Kx^{\beta_1}N(d_{\beta_1}) + \frac{F^2k_r}{2r}\left(1 - e^{-rT}(1 - N(d_0))\right)$$
$$-Bx^{\beta_2}N(d_{\beta_2}) - \frac{\alpha x^2}{R}e^{-RT}N(d_2) + \frac{\alpha x^2}{R}e^{-RT}\Big] =$$
$$= Kx^{\beta_1} + \frac{F^2k_r}{2r} \tag{B.11}$$

Hence the same result for perpetual option

$\lim_{T\to+\infty}$ for $x > x_F$

$$\lim_{T\to+\infty}\Big[-Kx^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F^2k_r}{2r}e^{-rT}(1 - N(d_0))$$
$$+Bx^{\beta_2}(1 - N(d_{\beta_2})) + \frac{\alpha x^2}{R}\left(1 - e^{-RT}N(d_2)\right) + \frac{\alpha x^2}{R}e^{-RT}\Big] =$$
$$= Bx^{\beta_2} + \frac{\alpha x^2}{R} \tag{B.12}$$

$$\lim_{T\to 0} d_0 = \begin{cases} -\infty & x < x_F \\ +\infty & x > x_F \end{cases} \tag{B.13}$$

$\lim_{T\to 0}$ for $x < x_F$

$$\lim_{T\to 0}\Big[Kx^{\beta_1}N(d_{\beta_1}) + \frac{F^2k_r}{2r}\left(1 - e^{-rT}(1 - N(d_0))\right)$$
$$-Bx^{\beta_2}N(d_{\beta_2}) - \frac{\alpha x^2}{R}e^{-RT}N(d_2) + \frac{\alpha x^2}{R}e^{-RT}\Big] = \frac{\alpha x^2}{R} \tag{B.14}$$

$\lim_{T\to 0}$ for $x > x_F$

$$\lim_{T\to 0}\Big[-Kx^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F^2k_r}{2r}e^{-rT}(1 - N(d_0))$$
$$+Bx^{\beta_2}(1 - N(d_{\beta_2})) + \frac{\alpha x^2}{R}\left(1 - e^{-RT}N(d_2)\right) + \frac{\alpha x^2}{R}e^{-RT}\Big] = \frac{\alpha x^2}{R} \tag{B.15}$$

Hence for both the $\lim_{T \to 0}$ is the value of the project without guarantee, in other words is the NPV.

Appendix C Investment thresholds

Appendix C.1 First interval: $x < x_F$

The value-matching condition is:

$$
\begin{aligned}
Ax^{*\beta_1} = {} & Kx^{*\beta_1}N(d_{\beta_1}) + \frac{F^2k_r}{2r}(1 - e^{-rT}(1 - N(d_0))) \\
& - Bx^{*\beta_2}N(d_{\beta_2}) - \frac{\alpha x^{*2}}{R}e^{-RT}N(d_2) + \frac{\alpha x^{*2}}{R}e^{-RT} - I \quad \text{(C.1)}
\end{aligned}
$$

The smooth-pasting condition is:

$$
\begin{aligned}
\beta_1 Ax^{*\beta_1 - 1} = {} & Kx^{*\beta_1}\frac{\partial N(d_{\beta_1})}{\partial p} + \beta_1 Kx^{*\beta_1 - 1}N(d_{\beta_1}) + \frac{F^2k_r}{2r}e^{-rT}\frac{\partial N(d_0)}{\partial p} \\
& - \beta_2 Bx^{*\beta_2 - 1}N(d_{\beta_2}) - Bx^{*\beta_2}\frac{\partial N(d_{\beta_2})}{\partial p} \\
& - \frac{2\alpha x^*}{R}e^{-RT}N(d_2) - \frac{\alpha x^{*2}}{R}e^{-RT}\frac{\partial N(d_1)}{\partial p} + \frac{2\alpha x^*}{R}e^{-RT} \quad \text{(C.2)}
\end{aligned}
$$

As in Shackleton & Wojakowski (2007) (Appendix B), the partial derivatives of the cumulative distribution function cancel across the betas, reducing the value-matching and smooth-pasting conditions to the following nonlinear equation:

$$
\begin{aligned}
& -(\beta_1 - \beta_2)Bx^{*\beta_2}N(d_{\beta_2}) - (\beta_1 - 2)\left(\frac{\alpha x^{*2}}{R}e^{-RT}N(d_2)\right) \\
& \qquad + \beta_1\left(\frac{F^2k_r}{2r}(1 - e^{-rT}(1 - N(d_0))) - I\right) \quad \text{(C.3)}
\end{aligned}
$$

Equation C.3 must be solved numerically to find optimal exercise threshold, x^*.

Appendix C.2 Second interval: $x > x_F$

The value-matching condition is:

$$
\begin{aligned}
A_1 p^{*\beta_1} = {} & -Kx^{*\beta_1}(1 - N(d_{\beta_1})) - \frac{F^2k_r}{2r}e^{-rT}(1 - N(d_0)) \\
& + Bx^{*\beta_2}(1 - N(d_{\beta_2})) + \frac{\alpha x^{*2}}{R}(1 - e^{-RT}N(d_2) + \frac{\alpha x^{*2}}{R}e^{-RT} - I \quad \text{(C.4)}
\end{aligned}
$$

The smooth-pasting condition is:

$$\beta_1 A_1 p^{*\beta_1 - 1} = -\beta_1 K x^{*\beta_1 - 1} N(d_{\beta_1}) - K x^{*\beta_1} \frac{\partial N(d_{\beta_1})}{\partial p} + e^{-rT} \frac{F^2 k_r}{2r} \frac{\partial N(d_0)}{\partial p}$$
$$+ \beta_2 B x^{*\beta_2 - 1}(1 - N(d_{\beta_2})) - B x^{*\beta_2} \frac{\partial N(-d_{\beta_2})}{\partial p}$$
$$+ \frac{2\alpha x^*}{R}(1 - e^{-RT} N(d_2)) - \frac{\alpha x^{*2}}{R} e^{-RT} \frac{\partial N(d_1)}{\partial p} + \frac{2\alpha x^*}{R} e^{-RT} \quad \text{(C.5)}$$

As before, the partial derivatives of the cumulative distribution function cancel across the betas, reducing the value-matching and smooth-pasting conditions to the following nonlinear equation:

$$(\beta_1 - \beta_2) B x^{*\beta_2}(1 - N(d_{\beta_2})) + (\beta_1 - 2)\left(\frac{\alpha x^{*2}}{R}(1 - e^{-RT} N(d_2))\right)$$
$$- \beta_1 \left(\frac{F^2 k_r}{2r} e^{-rT}(1 - N(d_0)) + I\right) \quad \text{(C.6)}$$

Equation C.6 must be solved numerically to find optimal exercise threshold, x^*.

Appendix D Value of the project for a finite FIT: Price taker

This is an extension of Shackleton & Wojakowski (2007) to a renewable energy project, where we include a FIT. The value of the project with perpetual guarantee is:

$$V(p_T,\infty) = \begin{cases} Kp^{\beta_1} + \dfrac{F}{r} & p < F \\ \\ Bp^{\beta_2} + \dfrac{p}{r-\mu} & p > F \end{cases} \tag{D.1}$$

Now, the value of the project is extended with finite guarantee. For more details see Appendix A of Shackleton & Wojakowski (2007).

$$V(p,T) = V(p,\infty) - V(p_T,\infty) = V(p,\infty) - e^{-rT}E_0^Q\left[V(p_T,\infty)\right] \tag{D.2}$$

$$V(p,\infty) = \left[Kp^{\beta_1} + \frac{F}{r}\right]1_{p<F} + \left[Bp^{\beta_2} + \frac{p}{r-\mu}\right]1_{p>F} \tag{D.3}$$

$$V(p_T,\infty) = \left[Kp_T^{\beta_1} + \frac{F}{r}\right]1_{p_T<F} + \left[Bp_T^{\beta_2} + \frac{p_T}{r-\mu}\right]1_{p_T>F} \tag{D.4}$$

$$d_\beta = \frac{\ln\dfrac{p}{F} + \left(\mu + \sigma^2\left(\beta - \dfrac{1}{2}\right)\right)T}{\sigma\sqrt{T}} \tag{D.5}$$

$$q(\beta) = \frac{1}{2}\sigma^2\beta(\beta-1) + \beta\mu - r \tag{D.6}$$

$$e^{-rT}E_0^Q\left[p_T^\beta 1_{p_T<F}\right] = e^{q(\beta)T}p^\beta N(-d_\beta) \tag{D.7}$$

$$e^{-rT}E_0^Q\left[p_T^\beta 1_{p_T>F}\right] = e^{q(\beta)T}p^\beta N(d_\beta) \tag{D.8}$$

$$
\begin{gathered}
\beta = \beta_1 \\
q(\beta_1) = 0 \\
d_{\beta_1} = \frac{\ln \dfrac{p}{F} + \left(\mu + \sigma^2\left(\beta_1 - \dfrac{1}{2}\right)\right)T}{\sigma\sqrt{T}} \\
e^{-rT}E_0^Q\left[Kp^{\beta_1}\right] = Kp^{\beta_1}N(-d_{\beta_1})
\end{gathered}
\tag{D.9}
$$

$$
\begin{gathered}
\beta = 0 \\
q(0) = -r \\
d_0 = \frac{\ln \dfrac{p}{F} + \left(\mu - \dfrac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} \\
e^{-rT}E_0^Q\left[\frac{F}{r}\right] = e^{-rT}\frac{F}{r}N(-d_0)
\end{gathered}
\tag{D.10}
$$

$$
\begin{gathered}
\beta = \beta_2 \\
q(\beta_2) = 0 \\
d_{\beta_2} = \frac{\ln \dfrac{p}{F} + \left(\mu + \sigma^2\left(\beta_2 - \dfrac{1}{2}\right)\right)T}{\sigma\sqrt{T}} \\
e^{-rT}E_0^Q\left[Bp^{\beta_2}\right] = Bp^{\beta_2}N(d_{\beta_2})
\end{gathered}
\tag{D.11}
$$

$$\beta = 1$$
$$q(1) = \mu - r$$
$$d_1 = \frac{\ln \frac{p}{F} + \left(\mu + \frac{\sigma}{2}\right) T}{\sigma \sqrt{T}}$$
$$e^{-rT} E_0^Q \left[\frac{p}{r - \mu} \right] = \frac{p}{r - \mu} N(d_1) e^{-(r-\mu)T} \quad \text{(D.12)}$$

Recall that $V(p, T) = V(p, \infty) - e^{-rT} E_0^Q [V(p_T, \infty)]$

For $p < F$

$$\begin{aligned} &Kp^{\beta_1} + \frac{F}{r} \\ &- \left[Kp^{\beta_1} N(-d_{\beta_1}) + \frac{F}{r} e^{-rT} N(-d_0) + Bp^{\beta_2} N(d_{\beta_2}) + \frac{p}{r - \mu} e^{-(r-\mu)T} N(d_1) \right] \end{aligned} \quad \text{(D.13)}$$

$N(-d_\beta) = 1 - N(d_\beta)$. Hence, for $p < F$

$$\begin{aligned} &Kp^{\beta_1} N(d_{\beta_1}) + \frac{F}{r} (1 - e^{-rT} (1 - N(d_0))) \\ &\qquad - Bp^{\beta_2} N(d_{\beta_2}) - \frac{p}{r - \mu} e^{-(r-\mu)T} N(d_1) \end{aligned} \quad \text{(D.14)}$$

For $p > F$

$$\begin{aligned} &Bp^{\beta_2} + \frac{p}{r - \mu} \\ &- \left[Kp^{\beta_1} N(-d_{\beta_1}) + \frac{F}{r} e^{-rT} N(-d_0) + Bp^{\beta_2} N(d_{\beta_2}) + \frac{p}{r - \mu} e^{-(r-\mu)T} N(d_1) \right] \end{aligned} \quad \text{(D.15)}$$

$$
\begin{aligned}
&- Kp^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r}e^{-rT}(1 - N(d_0)) \\
&\qquad\qquad + Bp^{\beta_2}(1 - N(d_{\beta_2})) + \frac{p}{r-\mu}(1 - e^{-(r-\mu)T}N(d_1))
\end{aligned}
\tag{D.16}
$$

$$
V^G(p) = \begin{cases}
Kp^{\beta_1}N(d_{\beta_1}) + \dfrac{F}{r}(1 - e^{-rT}(1 - N(d_0))) & \\
\qquad -Bp^{\beta_2}N(d_{\beta_2}) - \dfrac{p}{r-\mu}e^{-(r-\mu)T}N(d_1) & p < F \\
& \\
-Kp^{\beta_1}(1 - N(d_{\beta_1})) - \dfrac{F}{r}e^{-rT}(1 - N(d_0)) & \\
\qquad +Bp^{\beta_2}(1 - N(d_{\beta_2})) + \dfrac{p}{r-\mu}(1 - e^{-(r-\mu)T}N(d_1)) & p > F
\end{cases}
\tag{D.17}
$$

Now, we add the part without guarantee

$$
V(p) = V^G(p) + \frac{p}{r-\mu}e^{-(r-\mu)T} \tag{D.18}
$$

Appendix E Limits of the value of project for a finite FIT: Price taker

Checking the limit for $T \to +\infty$

$$\lim_{T\to+\infty} d_0 = \lim_{T\to+\infty} \frac{\ln\frac{p}{F} + \left(\mu - \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = \begin{cases} -\infty & \mu - \frac{\sigma^2}{2} < 0 \\ +\infty & \mu - \frac{\sigma^2}{2} > 0 \end{cases} \tag{E.1}$$

$$\lim_{T\to+\infty} d_1 = \lim_{T\to+\infty} \frac{\ln\frac{p}{F} + \left(\mu + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}} = +\infty \tag{E.2}$$

$$\lim_{T\to+\infty} d_{\beta_1} = \lim_{T\to+\infty} \frac{\ln\frac{p}{F} + \left(\mu + \sigma^2\left(\beta_1 - \frac{1}{2}\right)\right)T}{\sigma\sqrt{T}} = +\infty \tag{E.3}$$

$$\lim_{T\to+\infty} d_{\beta_2} = \lim_{T\to+\infty} \frac{\ln\frac{p}{F} + \left(\mu + \sigma^2\left(\beta_2 - \frac{1}{2}\right)\right)T}{\sigma\sqrt{T}} = -\infty \tag{E.4}$$

Recall that $\beta_2 < 0$ and $\beta_1 > 1$. In addition, β_1 and β_2 is the solution of the following quadratic equation: $0.5\sigma^2\beta(\beta-1)+\mu\beta-r$. Hence $\lim_{T\to+\infty} d_{\beta_2}$ is always $-\infty$. In addition, $N(+\infty) = 1$ and $N(-\infty) = 0$.

$\lim_{T\to+\infty}$ for $p < F$

$$\lim_{T\to+\infty} \Bigg[Kp^{\beta_1}N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ -Bp^{\beta_2}N(d_{\beta_2}) - \frac{p}{r-\mu}e^{-(r-\mu)T}N(d_1) + \frac{p}{r-\mu}e^{-(r-\mu)T}\Bigg] = \\ = Kp^{\beta_1} + \frac{F}{r} \tag{E.5}$$

Hence the same result for perpetual option

$\lim_{T\to+\infty}$ for $p > F$

$$\lim_{T\to+\infty}\Bigg[-Kp^{\beta_1}(1-N(d_{\beta_1}))-\frac{F}{r}e^{-rT}(1-N(-d_0))$$
$$+Bp^{\beta_2}(1-N(d_{\beta_2}))+\frac{p}{r-\mu}(1-e^{-(r-\mu)T}N(d_1))+\frac{p}{r-\mu}e^{-(r-\mu)T}\Bigg]=$$
$$=Bp^{\beta_2}+\frac{p}{r-\mu} \quad \text{(E.6)}$$

Checking the limit for $T\to 0$

$$\lim_{T\to+0}d_0=\begin{cases}-\infty & p<F\\ \\ +\infty & p>F\end{cases} \quad \text{(E.7)}$$

$\lim_{T\to 0}$ for $p<F$

$$\lim_{T\to 0}\Bigg[Kp^{\beta_1}N(d_{\beta_1})+\frac{F}{r}(1-e^{-rT}(1-N(d_0)))$$
$$-Bp^{\beta_2}N(d_{\beta_2})-\frac{p}{r-\mu}e^{-(r-\mu)T}N(d_1)+\frac{p}{r-\mu}e^{-(r-\mu)T}\Bigg]=$$
$$=\frac{p}{r-\mu} \quad \text{(E.8)}$$

$\lim_{T\to 0}$ for $p>F$

$$\lim_{T\to 0}\Bigg[-Kp^{\beta_1}(1-N(d_{\beta_1}))-\frac{F}{r}e^{-rT}(1-N(-d_0))$$
$$+Bp^{\beta_2}(1-N(d_{\beta_2}))+\frac{p}{r-\mu}(1-e^{-(r-\mu)T}N(d_1))+\frac{p}{r-\mu}e^{-(r-\mu)T}\Bigg]=$$
$$=\frac{p}{r-\mu} \quad \text{(E.9)}$$

Hence for both the $\lim_{T\to 0}$ is the value of the project without guarantee, in other words is the NPV.

Appendix F Investment thresholds: Price taker

Appendix F.1 First interval: $p < F$

The value-matching condition is:

$$
\begin{aligned}
Ap^{*\beta_1} = {} & Kp^{*\beta_1}N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\
& - Bp^{*\beta_2}N(d_{\beta_2}) - \frac{p^*}{r-\mu}e^{-(r-\mu)T}N(d_1) + \frac{p^*}{r-\mu}e^{-(r-\mu)T} - I
\end{aligned} \tag{F.1}
$$

The smooth-pasting condition is:

$$
\begin{aligned}
\beta_1 Ap^{*\beta_1 - 1} = {} & Kp^{*\beta_1}\frac{\partial N(d_{\beta_1})}{\partial p} + \beta_1 Kp^{*\beta_1 - 1}N(d_{\beta_1}) + \frac{F}{r}e^{-rT}\frac{\partial N(d_0)}{\partial p} \\
& - \beta_2 Bp^{*\beta_2 - 1}N(d_{\beta_2}) - Bp^{*\beta_2}\frac{\partial N(d_{\beta_2})}{\partial p} \\
& - \frac{1}{r-\mu}e^{-(r-\mu)T}N(d_1) - \frac{p^*}{r-\mu}e^{-(r-\mu)T}\frac{\partial N(d_1)}{\partial p} \\
& + \frac{1}{r-\mu}e^{-(r-\mu)T}
\end{aligned} \tag{F.2}
$$

As in Shackleton & Wojakowski (2007) (Appendix B), the partial derivatives of the cumulative distribution function cancel across the betas, reducing the value-matching and smooth-pasting conditions to the following nonlinear equation:

$$
\begin{aligned}
& -(\beta_1 - \beta_2)Bp^{*\beta_2}N(d_{\beta_2}) - (\beta_1 - 1)\left(\frac{p^*}{r-\mu}e^{-(r-\mu)T}N(d_1)\right) \\
& + \beta_1\left(\frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) - I\right)
\end{aligned} \tag{F.3}
$$

Equation F.3 must be solved numerically to find optimal exercise threshold, p^*.

Appendix F.2 Second interval: $p > F$

The value-matching condition is:

$$
\begin{aligned}
A_1 p^{*\beta_1} = {} & -Kp^{*\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r}e^{-rT}(1 - N(d_0)) \\
& + Bp^{*\beta_2}(1 - N(d_{\beta_2})) + \frac{p^*}{r-\mu}(1 - e^{-(r-\mu)T}N(d_1) + \frac{p^*}{r-\mu}e^{-(r-\mu)T} - I
\end{aligned} \tag{F.4}
$$

The smooth-pasting condition is:

$$\begin{aligned}\beta_1 A_1 p^{*\beta_1 - 1} = -\beta_1 K p^{*\beta_1 - 1} N(d_{\beta_1}) - K p^{*\beta_1} \frac{\partial N(d_{\beta_1})}{\partial p} + e^{-rT} \frac{F}{r} \frac{\partial N(d_0)}{\partial p} \\ + \beta_2 B p^{*\beta_2 - 1}(1 - N(d_{\beta_2})) - B p^{*\beta_2} \frac{\partial N(-d_{\beta_2})}{\partial p} \\ + \frac{1}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) - \frac{p^*}{r-\mu} e^{-(r-\mu)T} \frac{\partial N(d_1)}{\partial p} \\ + \frac{1}{r-\mu} e^{-(r-\mu)T}\end{aligned} \tag{F.5}$$

As before, the partial derivatives of the cumulative distribution function cancel across the betas, reducing the value-matching and smooth-pasting conditions to the following nonlinear equation:

$$\begin{aligned}(\beta_1 - \beta_2) B p^{*\beta_2}(1 - N(d_{\beta_2})) + (\beta_1 - 1)\left(\frac{p^*}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1))\right) \\ - \beta_1 \left(\frac{F}{r} e^{-rT}(1 - N(d_0)) + I\right)\end{aligned} \tag{F.6}$$

Equation F.6 must be solved numerically to find optimal exercise threshold, p^*.

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