Feed-in Tariffs with Minimum Price Guarantees and Regulatory Uncertainty

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Abstract

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 investors. This paper presents a novel model to analyze a FIT contract with a minimum price guarantee (i.e., a price-floor regime) from an investor's perspective. The results show that a perpetual guarantee only induces investment for prices below the price floor when offering a risk-free investment opportunity. In contrast, the finite guarantee may induce investment even when the revenue from the guarantee is lower than the investment cost. When an investor faces a scenario with regulatory uncertainty, a higher and more likely reduction in the price floor induces earlier investment. For all cases, investors postpone an investment decision when market conditions present a higher price volatility.

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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 because these resources may not be available for future generations. Therefore, policymakers can incentivize energy generation through renewable resources, and consequently decrease the social cost of scarcity and prices of resources while social welfare increases.

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. 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 programs are long-term contracts with renewable energy producers (e.g., homeowners, firms and organizations such as schools and community groups) to enhance energy generation.

In addition, Couture & Gagnon (2010) present many different remuneration schemes used by policymakers that have evolved over time. FIT policies can be classified into two groups. The first group, also known as market-independent FIT, uses a fixed-price policy, where the remuneration is independent from the electricity market price. The second group is a premium-price policy, also known as market-dependent FIT, because a premium payment is added to the electricity market price. The market-independent FITs have been widely employed in many countries, because these policies create a lower risk investment condition. In contrast, market-dependent FITs present a greater risk for investors but also create an incentive to produce more electricity when it is needed most and provide slightly higher income to investors (Schallenberg-Rodriguez & Haas 2012). Market-dependent FITs have been implemented in Spain, Germany and Denmark, among other countries.

Since the inception of the first FIT program in 1978, policymakers have constantly reviewed FIT schemes in order to achieve specific energy policy goals. Ritzenhofen & Spinler (2016) present many reasons for these reviews. For example, policymakers are constantly trying to find more efficient schemes aimed at promoting renewable energy investments. Another important reason for reviewing the scheme is to find a cost-effective policy that is accepted by society and is subject to budget constraints. Hence, investors must take into account the risk of policy reductions within the decision-making process of a renewable energy project.

This article presents a real options model to analyze a FIT with a minimum price guarantee (i.e., a price-floor regime) in two scenarios, namely a perpetual guarantee and a finite guarantee. Within this policy, a producer either receives a fixed amount if the market price is below the price floor or the market price when the price is above the price floor. This FIT design is considered a variable-premium FIT according to Couture & Gagnon (2010) and is also known as minimum payment guarantee, minimum price policies or spot market gap model (Couture, Kreycik & Williams 2010) . In particular, variations of the minimum price guarantee have been used in the Netherlands (Couture et al. 2010), Ireland (Doherty & O'Malley 2011) and Switzerland (Couture et al. 2010). We then continue the analysis in a scenario that includes a regulatory uncertainty, whereby the price floor may decrease.

Our model includes managerial flexibilities and computes the optimal investment threshold based on an analytical real options framework. We use the model to analyze how the price floor, its duration and policy uncertainty before the project starts affect the investment threshold and the value of the project. Not only may this analysis provide insights to investors (e.g., regarding optimal investment timing and value of the project), but also to policymakers (e.g., regarding FIT design).

The results show that a perpetual guarantee is not economically sound. This is due to the fact that a perpetual guarantee can only induce investment for prices below the price floor when the revenue from the guarantee is higher than the investment cost. Apparently, this is a counter-intuitive result due to the perpetual guarantee, which is not foregone if investment does not occur. On the other hand, for the finite scenario, the guarantee can induce investment for prices below the price floor when the revenue is below the investment cost. In addition, the finite guarantee induces an earlier investment decision as we increase the price floor and duration.

Considering the risk of reduction on the price floor due to regulatory uncertainty, the perpetual guarantee continues to induce investment only for prices below the price floor when a risk-free investment opportunity is offered. The results also show that either greater changes in the price floor or higher probabilities of a reduction occurring on the price floor lead to lower investment thresholds. This is due to the fact that investors accelerate investment in order to guarantee a higher price floor.

This paper is organized as follows. Section 2 presents the related work and our main contributions to literature. Section 3 presents the model and analysis of a FIT with a minimum price guarantee, where we present the perpetual and finite guarantee cases. Section 4 presents an extension of our model where we include regulatory uncertainty. Finally, Section 5 presents discussion and concluding remarks.

2 Related Work

There is a large set of topics related to the work presented in this paper. We broadly group these into two main categories: work related to FITs and support schemes for renewable energy projects, and work related to real options approaches applied to energy investment.

2.1 FIT and Support Schemes for Renewable Energy Projects

Many research works have been carried out to discuss a multitude of policy mechanisms to accelerate the investment in renewable energy projects. For example, Abolhosseini & Heshmati (2014) compare three widely used support schemes for renewable energy projects, namely FITs, tax incentives and renewable portfolio standard. As previously stated, FITs are long-term contracts that are price-based incentives. Tax incentives are fiscal incentives (e.g., subsidies and tax deductions) to enhance renewable energy deployment. Renewable Portfolio Standard (RPS) is a quantity-based incentive whereby utility companies have to increase the production from designated renewable energy sources (i.e., an obligation to produce a specified fraction from designated renewable sources). For every unit of renewable energy produced, the utilities receive a tradable green certificate. Utilities that generate more renewable electricity than required by the RPS obligation may sell (or trade) the certificates to other utilities that have not achieved their own RPS obligation. The regulatory body then receives these certificates in order to determine whether utilities are compliant with their RPS obligations. The work draws three main conclusions. First, investors prefer fixed-price FITs when they are seeking schemes with a lower risk. Second, tax incentives can also attract investors because they make cash available (i.e., increases investor liquidity). Third, the implementation of RPS relies on a private market for utilities to trade certificates. Thus, this market-based policy may lead to price competition and consequently more efficient energy markets. Butler & Neuhoff (2008) compare different support schemes for renewable energy projects in the UK and Germany. The authors state that FITs in Germany are more effective in promoting the deployment of renewable energy projects than other support schemes in the UK (i.e., Non-Fossil Fuel Obligation and Renewables Obligation Certificates).

In 1978, FIT was first implemented as part of the US Public Utility Regulatory Policies Act. Many authors (e.g., Couture & Gagnon (2010) and Lesser & Su (2008)) claim that FITs are the most successful support scheme for incentivizing renewable energy projects. Lesser & Su (2008) state that FITs require policymakers to define many attributes such as payment amounts for different technologies (e.g. wind power or solar photovoltaics), payment structures (e.g., fixed payment or premium over market prices), and payment duration. Since FITs are long-term contracts (typically 20 years), policymakers have to use forecasts of future market conditions and rates of technological improvements in order to define these attributes. However, long-term forecasts are typically inaccurate and imprecise due to the high uncertainty that affects the market and technology. From an investor's perspective, the definition of these attributes can have a big impact on the decision-making process of investing in a renewable energy project.

Regarding research work on FITs, Couture & Gagnon (2010) present many different remuneration schemes utilized by policymakers that have evolved over time. All these remuneration schemes can be classified into two groups: (i) Market-independent FIT - a fixed-price policy, where the remuneration is independent from the electricity market price, and (ii) Market-dependent FIT - a premium-price policy, where the remuneration is set by premium payments tied to the electricity market price. The work states that market-independent FITs increase investment security and hence attract more investors. In contrast, market-dependent FITs are market-based mechanisms that create incentives to produce energy when demand is high. However, both market-independent and market-dependent FITs (in particular, the fixed-premium schemes) may lead to either over or under compensation. The work suggests that variable-premium FITs, with caps and floors within the FIT structure, integrate the strengths of both market dependent and independent policies. Schallenberg-Rodriguez & Haas (2012) present a review of the implementation of the fixed-price and variable-premium FITs in Spain. The authors claim that fixed-price policies are more adequate to small investors and less-mature technologies while variable-premium polices are indicated for large investors and mature technologies.

Market-independent FITs have the key advantage of creating conditions for a secure investment, where price risk is removed and costs of financing are more likely to be reduced (Couture et al. 2010). FITs with a minimum price guarantee also share the same condition when the market price is below the price floor. However, this condition for a secure investment may disappear if policymakers set the price floor with very low values, whereby investors will hardly receive the payments from the guarantee. Market-dependent FITs have the key advantage of creating incentives to produce energy when demand is high (Couture & Gagnon 2010). This feature is also present in FITs with a minimum price guarantee when the market price is above the price floor. However, setting price floors with high values removes this incentive. From a policy-making perspective, the key challenges of FITs with a price floor is actually deciding the value of the price floor and duration of the guarantee, while trying to maintain the key features of market-independent and market-dependent FITs. Our work sheds some light to policymakers regarding the decision of defining the price floor and duration of the guarantee and how this can impact the investment decision.

In Ireland, the REFIT 1, 2, and 3 (DCCAE 2016) are variable-premium FITs that are comprised of the following elements: (i) Price floor - The contract applies an indexed price floor, called the reference price, on the annual market price revenue. In other words, if an annual market revenue is below a revenue yielded by the price floor, the Public Service Obligation (PSO) mechanism will refund the difference. In particular, each technology category (e.g., wind or biomass) has a different indexed price floor in order to support technologies with different cost levels. (ii) Balancing Payment - Under REFIT 1, the PSO gives an additional payment (15% of the indexed price floor), irrespective of the market price or technology. Under REFIT 2 and 3, the PSO gives an additional payment of up to a maximum of €9.90 per MWh, whereby the payment only applies when the market price is lower than the combination of the indexed price floor plus the balancing payment. A few papers have analyzed the Irish REFIT scheme. For example, scholars have analyzed the impact of the REFIT policy on biomass crops (Clancy, Breen, Thorne & Wallace 2012) and wave power (Deane, Dalton & Gallachóir 2012).

While many research works have focused on discussing different policies and design options for FITs, only few analytical approaches are presented to analyze FIT policies and the impact on renewable energy projects from an investor's perspective. With an analytical approach, managers can obtain important information regarding the renewable energy project, such as the investment threshold and the value of the project.

2.2 Real Option Approaches for Energy Investments

The term real options was coined by Myers (1977) and provides a methodology to better value investment projects in the presence of managerial flexibilities. The real options framework was introduced by Tourinho (1979), which analyzes the option to extract oil when future prices are uncertain. Brennan & Schwartz (1985) also present one of the first contributions to the real options literature tailored for mineral extraction investments. McDonald & Siegel (1986) derived the optimal investment rule which takes into account the value of waiting. They showed that the standard net present value (NPV) analysis is grossly wrong.

Investment decisions in the corporate world are normally based on the NPV rule, whereby a project with a positive NPV is accepted. However, the standard NPV valuation underestimates the value of the project as the method does not take into account uncertainties and managerial flexibilities that are present in dynamic environments. For instance, a project with a negative NPV may lead to a successful investment, because the NPV does not include the value of important decisions that managers use in practice, such as gathering information from the market and waiting to invest until market conditions are favorable. Hence, the real options approach provides a good framework for valuations of renewable energy projects, since managerial flexibilities and uncertainties are incorporated into the model.

Power generation projects have several uncertainties, such as market price uncertainty and regulatory uncertainty. In addition, the investment in power generation is irreversible and has several managerial flexibilities. In fact, Ceseña, Mutale & Rivas-Dávalos (2013) state that real option approaches can be very useful for analyzing energy generation projects, especially renewable energy projects. Their work concludes that many research opportunities are still available regarding the application of real options theory to the renewable energy field.

Regarding real options research in the energy field, Boomsma, Meade & Fleten (2012) value investments from renewable energy sources in order to examine investment behavior under different investment schemes, namely FITs (fixed price and fixed premium) and renewable energy certificate trading. With a case study on wind power generation, the work shows that fixed-price FITs create incentives for speeding up investment while the certificate trading is more appropriate for larger projects. Abadie, Chamorro & González-Eguino (2013) determine the optimal time to invest in energy efficiency (EE) enhancements within a firm and the impact that some policy measures may have on the time to invest. The results show that policies for EE may bring the time to invest some years forward. Adkins & Paxson (2016) examine different government subsidy arrangements (e.g., permanent and retractable) and the impact on the optimal time to invest. The authors conclude that subsidies can encourage early investment, especially permanent subsidies.

Ritzenhofen & Spinler (2016) investigate the effect of regulatory uncertainty on the investment behavior. In particular, the work analyzes three scenarios. First, a fixed-price FIT where payments do not change over time. Second, a free-market regime where electricity is sold on the spot market. Third, a regime switching scenario where jurisdictions may switch from a fixed-price FIT to a free-market regime (or the reverse case), thus creating regulatory uncertainty. The results show that regulatory uncertainty delays or even reduces investment when fixed-FIT price is close to market price. In a scenario where the market price is significantly higher than the fixed-FIT price, investment is then accelerated. While this work also takes into consideration the effect of a regulatory uncertainty, it does not analyze a price-floor regime where a regulator may reduce the price floor at any time before the signature of the contract. In addition, the work models the regulatory uncertainty with a numerical approach (i.e., lattice-based method), while our work uses an analytical real options framework.

Boomsma & Linnerud (2015) use an analytical real options framework to analyze the effect of market and policy uncertainties on a renewable investment decision with three different subsidies. Depending on the policy scheme, the model may use a stochastic price and stochastic subsidy. In particular, the fixed-price FIT has no uncertainty, the fixed-premium FIT has a stochastic price and the green certificate scheme has both stochastic price and stochastic subsidy. The work claims that the difference between the risk of a market-based support scheme (i.e., tradable green certificates) and a fixed-price FIT is less than commonly expected, given that the electricity and subsidy prices are not perfectly correlated. The authors also argue that policy uncertainty (i.e., scheme termination) increases the investment threshold and consequently slows down investment when the termination decision is retroactively applied to new and old installations. When the decision is not retroactively applied, the termination decision speeds up investment. In comparison to our work, the model does not analyze a subsidy with a minimum price guarantee and the regulatory uncertainty only considers a scheme termination, while our work analyzes a scenario where the subsidy may be reduced.

Doherty & O'Malley (2011) analyze the Irish REFIT program with a real options approach. In particular, the work uses a Generalized Extreme Value distribution to forecast the mean expected market value of wind and the value of the put option (given a strike price). With these forecasts, the authors calculate the mean expected market value of wind with a price floor and balancing payment. Consequently, the work analyzes the efficiency of the Irish scheme. From a policy-making perspective, Kim & Lee (2012) analyze four different FIT schemes (i.e., fixed price, fixed-premium, minimum price guarantee, sliding premium) with a real options numerical technique (i.e., binomial lattice and simulation). Although the two previous works also analyze a FIT with a minimum price guarantee, the findings are focused on the efficiency of the schemes from a policy-making viewpoint and are not based on an analytical real options framework. With an analytical approach, the analysis could take into consideration important information regarding the investment decision, such as the optimal investment threshold.

To the best of our knowledge, our paper presents the first research work regarding an analytical model of a FIT with a minimum price guarantee, which can be used to derive the option value and the optimal investment threshold. In addition, we also compare a finite and perpetual support scheme in order to draw conclusions for both investors and policymakers. We then continue the analysis in order to include a regulatory uncertainty.

In fact, our model relates and contributes to the literature in several ways. Our first contribution is to the real option community, where we build on the work from Shackleton & Wojakowski (2007) in order to derive an analytical model of a FIT with a finite guarantee. Within this research community, the closest work to ours is the paper from Adkins & Paxson (2017), which uses an analytical framework to analyze a Public-Private Partnership arrangement with a perpetual floor and ceiling. Our work departs from the perpetual analysis in order to analyze a more realistic scenario with a finite duration of a price floor and regulatory uncertainty.

Our second contribution is to the energy research community, where we present a powerful model of a variable-premium FIT with a price-floor regime. The model takes into account managerial flexibilities and uncertainties within two different scenarios, namely a perpetual and finite guarantee. We show how this support scheme may affect the investment decision in renewable energy projects. We extend the analysis in order to include a regulatory uncertainty. In particular, we show how the probability of changing the support scheme affects the value of the option and investment threshold.

3 Modeling a FIT with a Minimum Price Guarantee

We analyze the renewable energy project from a single investor's perspective. The investor aims to optimize the project value of the investment, taking into consideration the uncertainties and managerial flexibilities.

In practice, investors use the NPV to value investment projects and usually assume that the project is always deployed after a fixed period of time. In contrast to the standard NPV valuation, the real options approach assumes that while time passes, the investor can gather information and revise assumptions about the future investment or contraction. In other words, more information is revealed while time passes, hence investors can make better decisions about future actions. The investor has therefore a waiting option to deploy the renewable energy project. This option to defer can add value to the project due to uncertainties (McDonald & Siegel 1986).

The most important options in our model are the following: (i) waiting option, where the investor has an option to wait to deploy the project when the market is favorable; and (ii) put options, where the investor has a set of options of selling energy for the price floor F instead of selling energy for the market price P; in other words, for any value of P at any time T, the option is exercised when F is greater than P.

In addition, we assume that the investment decision is applicable to all kinds of renewable energy projects, such as wind power or solar photovoltaic. The following subsections present two different scenarios of FIT contracts with a minimum price guarantee, namely a perpetual and finite guarantee.

3.1 Perpetual Guarantee

We start assuming that the FIT contract has a perpetual guarantee. Consequently, an investor may receive payments from the guarantee for the entire lifetime of the project and not for all future projects. Although a FIT contract with a perpetual guarantee is not used by any jurisdiction, this scenario is interesting to analyze and compare with the finite guarantee, which is a more realistic assumption. The FIT contract is based on a price-floor regime. In other words, the investor (or producer) receives the price floor F for every unit of energy produced, when the market price P is below the price floor. When the market price is above the price floor, the producer receives the market price.

We assume that the energy market price P follows a Geometric Brownian Motion (GBM) in Equation 1, which is the usual assumption in real options models. According to Pindyck (2001), while the GBM might not be the most accurate process for representing spot market prices of commodities, it is analytically convenient in real option models. In fact, Lo & Wang (1995) show that the GBM in real option applications typically generate small errors due to the long duration of the projects. Other research works on renewable energy investment (e.g., Ritzenhofen & Spinler (2016) and Boomsma et al. (2012)) have used this assumption.

$$dP = \mu P dt + \sigma P dW \tag{1}$$

where $\mu < r$ is a deterministic drift under the risk neutral measure of the future market electricity price, r is the risk-free interest rate, $\sigma > 0$ is the volatility, and dW is the standard Brownian motion process.

Let $V(P, F)$ be the value of the project. Applying Itô's Lemma (Dixit & Pindyck 1994) lead us to the Ordinary Differential Equation (ODE):

$$\mu \, P \frac{\partial V(P,F)}{\partial P} + 0.5\sigma^2 \, P^2 \, \frac{\partial^2 V(P,F)}{\partial P^2} - rV(P,F) + \Pi(P,F) = 0 \tag{2}$$

where $\Pi(P, F)$ is a perpetual profit flow of the renewable energy project with a FIT. Hence, the profit flow yields F, when the market price is below the price floor F of the FIT. Otherwise, the profit flow yields P, when the market price is above the price floor of the FIT.

$$\Pi(P,F) = Max(P,F) \tag{3}$$

In Equation 3, we assume that P is a revenue for one unit of energy and F is a revenue from the guarantee for one unit of energy. However, one can easily convert these parameters for an annual production by multiplying these unit values by the quantity of energy produced in a year. An example of a conversion is presented in Section 3.3 where we use annualized values. In addition, we assume that the production cost has zero marginal cost, based on the data from the US Energy Information Administration (EIA 2017).

And the general solution to the ODE in Equation 2 is given by:

$$V(P,F) = \begin{cases} A_1 P^{\beta_1} + A_2 P^{\beta_2} + \dfrac{F}{r} & \text{for } P < F \\ \\ B_1 P^{\beta_1} + B_2 P^{\beta_2} + \dfrac{P}{r-\mu} & \text{for } P \geqslant F \end{cases} \tag{4}$$

where A_1, A_2, B_1 and B_2 are constants that are yet to be determined through economic boundary conditions. In addition, $\beta_1 > 1$ and $\beta_2 < 0$ are the solutions to the following quadratic equation:

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

Hence,

$$\beta_1=\frac{1}{2}-\frac{\mu}{\sigma^2}+\left(\left(-\frac{1}{2}+\frac{\mu}{\sigma^2}\right)^2+\frac{2r}{\sigma^2}\right)^{\frac{1}{2}} \tag{6}$$

$$\beta_2=\frac{1}{2}-\frac{\mu}{\sigma^2}-\left(\left(-\frac{1}{2}+\frac{\mu}{\sigma^2}\right)^2+\frac{2r}{\sigma^2}\right)^{\frac{1}{2}} \tag{7}$$

We now present the three boundary conditions to determine the constants A_1, A_2, B_1 and B_2. First, note that for the region where the market price is below the price floor, the value of the project should converge to $\frac{F}{r}$ when P goes to zero. However, this only happens if A_2 is zero because $\beta_2 < 0$.

Second, in the region where the market price is above the price floor, the value of the project should converge to $\frac{P}{r-\mu}$ when P goes to infinity. However, if B_1 is different from zero and P goes to infinity, the function $V(P,F)$ would blow out because $\beta_1 > 1$. Hence, B_1 should be zero and the value of the project is:

$$V(P,F)=\begin{cases} A_1P^{\beta_1}+\dfrac{F}{r} & \text{for } P<F \\ \\ B_2P^{\beta_2}+\dfrac{P}{r-\mu} & \text{for } P\geqslant F \end{cases} \tag{8}$$

In the first branch (i.e., $P < F$), note that the term $\frac{F}{r}$ is equal to the value of the project if the investor receives a constant cash flow F. The term $A_1P^{\beta_1}$ is an added value that captures the option of receiving an extra cash flow when the market price is above the guarantee. Similarly in the second branch (i.e., $P \geqslant F$), the term $\frac{P}{r-\mu}$ is equal to the value of the project if the investor only sells energy in the market for a price P. The term $B_2P^{\beta_2}$ captures the option of receiving the price floor when the market price falls below the guarantee.

The third boundary condition is when the two regions above meet (i.e., $P = F$). In addition, $V(P,F)$ must be continuously differentiable across F. Equating the values and derivatives gives:

$$A_1=\frac{F^{1-\beta_1}}{\beta_1-\beta_2}\left(\frac{\beta_2}{r}-\frac{\beta_2-1}{r-\mu}\right) \tag{9}$$

$$B_2=\frac{F^{1-\beta_2}}{\beta_1-\beta_2}\left(\frac{\beta_1}{r}-\frac{\beta_1-1}{r-\mu}\right) \tag{10}$$

Assuming that an investor has a perpetual option to invest for a sunk cost of I, we can now find the value of the option to invest $F(P,F)$ together with the optimal investment rule. We know that the price P follows a geometric Brownian motion, hence we can follow the same steps to calculate the value of the project in order to find the value of the option. In other words, the solution of the ODE (Equation 2 without the perpetual profit flow) leads to a value of the option that is given by:

$$F(P,F)=C_1P^{\beta_1}+C_2P^{\beta_2} \tag{11}$$

We now apply a boundary condition in order to calculate C_2. We know that $F(0) = 0$ when $P = 0$, because $P = 0$ is an absorbing barrier. However, $F(0)$ is only zero when $C_2 = 0$, because $\beta_2 < 0$. Hence, the value of the option to invest is given by:

$$F(P, F) = C_1 P^{\beta_1} \tag{12}$$

It is straightforward to show that the value-matching and smooth-pasting conditions are not met for the first branch of Equation 8 (i.e., $P < F$). Hence, investment never occurs in this region, except when $\frac{F}{r} > I$, for which the investment occurs immediately and generates a risk-free payoff (i.e., a positive net present value (NPV) for every P). This apparently counter-intuitive result is due to the perpetual guarantee, which is not foregone if investment does not occur.

The value-matching and smooth-pasting conditions for $P \geqslant F$ are presented in Equations 13 and 14. The value-matching condition (Equation 13) is the optimal investment point where the value of the option (Equation 12) is equal to the value of the project (Equation 8, when $P \geqslant F$) minus the investment cost. In other words, the investor is indifferent between holding the option or deploying the project. The smooth-pasting condition (Equation 14) is a requirement whereby the value of the option and the value of the project meet tangentially (i.e., both have the same slope) at the optimal investment point. Hence, we calculate the first derivatives of both sides of Equation 13 with respect to the threshold for investment P^*, which yields Equation 14.

$$C_1 {P^*}^{\beta_1} = V(P^*, F) - I = B_2 {P^*}^{\beta_2} + \frac{P^*}{r - \mu} - I \tag{13}$$

$$C_1 \beta_1 {P^*}^{\beta_1 - 1} = B_2 \beta_2 {P^*}^{\beta_2 - 1} + \frac{1}{r - \mu} \tag{14}$$

From Equation 13, we isolate C_1 such that $C_1 = \dfrac{V(P^*, F) - I}{{P^*}^{\beta_1}}$.Then, we substitute C_1 in Equation 12 which yields the first branch (i.e., $P < P^*$) of Equation 15. The second branch (i.e., $P \geqslant P^*$) of Equation 15 is an immediate investment, where the value of the option is equal to the NPV (i.e., $V(P, F) - I$). Hence, Equation 15 presents the value of the option to invest:

$$F(P, F) = \begin{cases} (V(P^*, F) - I) \left(\dfrac{P}{P^*}\right)^{\beta_1} & \text{for } P < P^* \\ \\ V(P, F) - I & \text{for } P \geqslant P^* \end{cases} \tag{15}$$

In addition, Equations 13 and 14 reduce to the following non-linear equation:

$$(\beta_1 - \beta_2) B_2 {P^*}^{\beta_2} + (\beta_1 - 1) \frac{P^*}{r - \mu} - \beta_1 I = 0 \tag{16}$$

We can thus calculate the trigger for investment P^*, when $P^* \geqslant F$, by numerically solving Equation 16.

In addition, we calculate an interesting point where the trigger P^* is equal to the price floor F. Substituting F for P^* in Equation 16 and substituting Equation 10 for B_2 in Equation 16 yields:

$$(\beta_1 - \beta_2) \frac{F^{1-\beta_2}}{\beta_1 - \beta_2} \left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r - \mu}\right) {F^*}^{\beta_2} + (\beta_1 - 1) \frac{F^*}{r - \mu} - \beta_1 I = 0 \tag{17}$$

Simplifying Equation 17 yields the following result:

$$F = rI \tag{18}$$

Equation 18 shows that $\frac{F}{r} - I = 0$ when the trigger P^* is equal to the price floor F. This means that values of $F \leqslant P^*$ yield $\frac{F}{r} - I \leqslant 0$ and values of $F \geqslant P^*$ yield $\frac{F}{r} - I \geqslant 0$. Hence, the values of the trigger in Equation 16 are only valid when $\frac{F}{r} - I \leqslant 0$ because $P^* \geqslant F$. In addition, we also conclude that investment only occurs for $P < F$ with a risk-free profit (i.e., a positive NPV or $\frac{F}{r} - I \geqslant 0$).

The next section studies the case of a finite-lived guarantee.

3.2 Finite Guarantee

In this section, we build on the work from Shackleton & Wojakowski (2007) to derive the value of a renewable energy project that has a FIT contract with a finite duration. Just like the perpetual scenario, an investor has the option to wait until the market conditions are favorable in order to deploy the project. However, the FIT contract has now a finite duration of T years. In other words, during T years, the investor (or producer) may earn F (i.e., price floor) for every unit of energy produced, if the market price P is below the price floor. As mentioned in the previous section, this is a more realistic assumption. The complete derivation is presented in Appendix A.

Equation 19 presents the value of the project until T, whereby the producer benefits from the finite guarantee of the FIT contract.

$$V_T(P,F) = \begin{cases} A_1 P^{\beta_1} N(d_{\beta_1}) + \dfrac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ \qquad -B_2 P^{\beta_2} N(d_{\beta_2}) - \dfrac{P}{r-\mu} e^{-(r-\mu)T} N(d_1) & \text{for } P < F \\ \\ -A_1 P^{\beta_1}(1 - N(d_{\beta_1})) - \dfrac{F}{r} e^{-rT}(1 - N(d_0)) \\ \qquad +B_2 P^{\beta_2}(1 - N(d_{\beta_2})) \\ \qquad +\dfrac{P}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) & \text{for } P \geqslant F \end{cases} \tag{19}$$

where $N(.)$ is the cumulative normal integral, A_1 and B_2 are defined by Equations 9 and 10, and

$$d_\beta = \frac{\ln \dfrac{P}{F} + \left(\mu + \sigma^2 \left(\beta - \dfrac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \tag{20}$$

where $\beta_1, \beta_2, 0$ and 1 can substitute β.

After the end date of the scheme, the producer receives a cash flow with a present value equal to $\dfrac{P}{r-\mu} e^{-(r-\mu)T}$, which corresponds to selling energy to the market for the remaining lifetime of the project . Hence, Equation 21 presents the value of the project, which includes the period with the FIT contract and thereafter.

$$V_F(P,F) = V_T(P,F) + \frac{P}{r-\mu} e^{-(r-\mu)T} \tag{21}$$

Note that the value of the project reduces to the present value $\frac{P}{r-\mu}$ when there is no guarantee (i.e., $F = 0$). In the case of a perpetual guarantee (i.e., $T = \infty$), the value of the project reduces to Equation 8.[1]

[1]Proof is presented in Appendix B.

We now calculate the value of the option to invest and the optimal investment rule. Equation 22 presents the value of the option to invest when $P < P^*$. The value of the option derives from a solution of the ODE and a boundary condition, following the same steps of the previous section.

$$F_F(P, F) = D_1 P^{\beta_1} \tag{22}$$

Next, we derive the value-matching and smooth-pasting conditions. Recall that the value-matching condition is the optimal investment point where the decision of holding the option or deploying the project is indifferent from the investor's perspective. And the smooth-pasting condition requires that the value of the option needs to be tangent to the value of the project at the optimal investment point. Therefore, we obtain the value-matching condition (Equation 23) and the smooth-pasting condition (Equation 24) by following the same steps of the previous section.

$$D_1 {P_F^*}^{\beta_1} = V_F(P_F^*, F) - I \tag{23}$$

$$\beta_1 D_1 {P_F^*}^{\beta_1 - 1} = \frac{\partial V_F(P_F^*, F)}{\partial P_F^*} \tag{24}$$

In addition, Equation 25 presents the value of the option to invest.

$$F_F(P, F) = \begin{cases} (V_F(P_F^*, F) - I)\left(\dfrac{P}{P_F^*}\right)^{\beta_1} & \text{for } P < P_F^* \\ \\ V_F(P, F) - I & \text{for } P \geqslant P_F^* \end{cases} \tag{25}$$

Equations 23 and 24 reduce to the following nonlinear equations, that must be solved numerically to find the investment threshold P_F^* (Appendix C):

$$\begin{cases} -(\beta_1 - \beta_2) B_2 {P_F^*}^{\beta_2} N(d_{\beta_2}) - (\beta_1 - 1)\dfrac{P_F^*}{r - \mu} e^{-(r-\mu)T}(N(d_1) - 1) \\ \qquad + \beta_1 \left(\dfrac{F}{r}(1 - e^{-rT}(1 - N(d_0))) - I\right) = 0 & \text{for } P_F^* < F \\ \\ (\beta_1 - \beta_2) B_2 {P_F^*}^{\beta_2}(1 - N(d_{\beta_2})) \\ \qquad + (\beta_1 - 1)\left(\dfrac{P_F^*}{r - \mu}(1 - e^{-(r-\mu)T} N(d_1)) + \dfrac{P_F^*}{r - \mu} e^{-(r-\mu)T}\right) \\ \qquad - \beta_1 \left(\dfrac{F}{r} e^{-rT}(1 - N(d_0)) + I\right) = 0 & \text{for } P_F^* \geqslant F \end{cases} \tag{26}$$

In order to find the value of F where both branches of Equation 26 have the same solution, we substitute F for P_F^* in the second branch :

$$(\beta_1 - \beta_2) B_2 F^{\beta_2}(1 - N(d_{\beta_2(P_F^* = F)})) + (\beta_1 - 1)\left(\frac{F}{r - \mu}(1 - e^{-(r-\mu)T} N(d_{1(P_F^* = F)})) + \frac{F}{r - \mu} e^{-(r-\mu)T}\right) - \beta_1 \left(\frac{F}{r} e^{-rT}(1 - N(d_{0(P_F^* = F)})) + I\right) = 0 \tag{27}$$

Where $d_\beta(P_F^* = F)$ is calculated from Equation 20 where $P_F^* = F$

$$d_\beta(P_F^* = F) = \frac{\left(\mu + \sigma^2\left(\beta - \frac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \tag{28}$$

Rearranging Equation 27 yields the following equation:

$$(\beta_1-\beta_2)B_2(1-N(d_{\beta_2(P_F^*=F)}))F^{\beta_2} + \left(\frac{(\beta_1-1)}{r-\mu}(1-e^{-(r-\mu)T}N(d_{1(P_F^*=F)})) + \frac{(\beta_1-1)}{r-\mu}e^{-(r-\mu)T} - \frac{\beta_1 e^{-rT}}{r}(1-N(d_{0(P_F^*=F)}))\right)F - \beta_1 I = 0 \quad (29)$$

Substituting Equation 10 for B_2 in Equation 29 yields:

$$\left(\left(\frac{\beta_1}{r}-\frac{\beta_1-1}{r-\mu}\right)(1-N(d_{\beta_2(P_F^*=F)})) + \frac{(\beta_1-1)}{r-\mu}(1-e^{-(r-\mu)T}N(d_{1(P_F^*=F)}) + e^{-(r-\mu)T}) - \frac{\beta_1 e^{-rT}}{r}(1-N(d_{0(P_F^*=F)}))\right)F - \beta_1 I = 0 \quad (30)$$

We can thus calculate the value of F with Equation 30. In fact, this is an interesting point of F from a policymaking perspective. If a policymaker sets the value of F above this point, an investor starts a project receiving a revenue from the guarantee instead of a revenue from the market price, because $P_F^* < F$. In addition, it is straightforward to show that Equation 30 converges to Equation 18 (i.e., the perpetual trigger when $P^* = F$) when $T \to +\infty$.

Another interesting point of F from a policymaking perspective is when the NPV of the investment is zero, because any value of F greater than this point generates a positive NPV regardless of the value of the market price P. Consequently, offering an F above this point makes the investment occur immediately and does not give the investor an option to wait.

In order to find this point, we calculate the NPV when $P = 0$. In other words, the NPV is the value of project with $P = 0$ (i.e., Equation 19) subtracted by the investment cost I, which yields Equation 31.

$$F = \frac{Ir}{(1-e^{-rT})} \quad (31)$$

Hence, for values of F greater than $\frac{Ir}{(1-e^{-rT})}$, investment occurs immediately and generates a risk free profit. In fact, policymakers should set the value of the price floor F between the value of F from Equation 30 and Equation 31, because this interval gives an investor a waiting option and the project starts with a revenue from the guarantee.

In addition, calculating the limit of Equation 31 when T goes to $+\infty$ is equal to Equation 18 (i.e., $F = rI$), which is the point where trigger P^* with a perpetual guarantee is equal to the price floor F and has a NPV equal to zero. Hence, the distance between the value of F from Equation 30 and Equation 31 goes to zero as T goes to $+\infty$. From a policymaking viewpoint, the interval that gives an investor a waiting option and provides a revenue from the guarantee when the project starts is inexistent in the perpetual guarantee.

3.3 Numerical Analysis

In this section, we present a comparative statics analysis of the main drivers of the option to invest in a renewable energy project. In particular, we analyze the behavior of the investment threshold P^* as we change the price floor F, the duration of the guarantee T, and the volatility of the price σ.

Despite the fact that our model is not tailored for any specific technology, we had to choose an example in order to numerically calculate the investment threshold. Hence, we decided to use a typical European onshore wind farm with 25 wind turbines (Enevoldsen & Valentine 2016). Each wind turbine has a capacity of 2 MW and a total investment cost of 1.5 Million Euros / MW, which is a reasonable estimate according to EWEA (2009). We also consider a capacity factor for each power plant to be 30% (i.e., average power generated is 30%) that lies within the 20% to 35% range estimates from EWEA (2009).

For simplicity's sake, we analyze the investment threshold for a turbine, but the results can be easily calculated for N turbines within a wind park. We also assume that our model uses annualized parameters. For example, in a scenario where the market price is below the price floor, a turbine yields an annual revenue of €131,400.00 (i.e., 30 % x 2 MWh x €25 / MWh x 24 hours x 365 days). Following the work by Ritzenhofen & Spinler (2016), we use the same GBM parameters that have been calculated from real data: a deterministic drift of 0% and volatility of 19%. Table 1 summarizes the base-case parameters of the numerical analysis.

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

r	risk-free rate	5%
F	price floor	€25 / MWh
T	finite duration of FIT	15 years
μ	deterministic drift	0%
σ	volatility	6%
I	total investment cost	€3 Millions

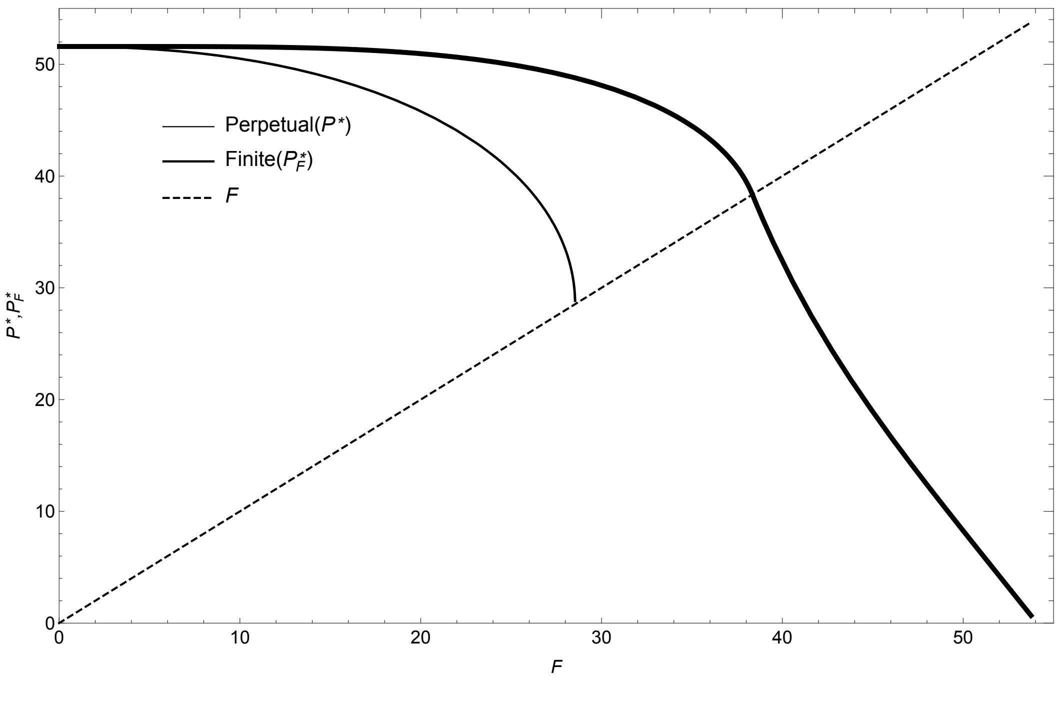

Figure 1: Investment thresholds (i.e., P^* and P_F^*) as a function of the minimum price guarantee (F)

Figure 1 presents the investment thresholds for a perpetual guarantee P^* (thin line) and for a finite guarantee P_F^* (thick line) as a function of the price floor F. The dashed line is the value of the price floor F, which divides the graph into two important regions.

First, the region above the dashed line represents a market condition where prices are above the price floor (i.e., $P > F$). Within this region, the triggers of the perpetual and finite guarantees decrease as the price floor increases. In other words, the triggers induce an earlier investment decision as we increase the price floor. From a policymaking perspective, values of the triggers that are greater than the price floor F create a scenario where a project starts receiving a revenue from the market price instead of the revenue from the guarantee. The project is also more likely to receive a revenue from the market price than the revenue from the guarantee throughout its lifetime. Hence, values of price floors in this region make the policy scheme practically useless. In Figure 1, the values of F in this region are between €0 / MWh and €28.54 / MWh for the perpetual guarantee. Note that the value of F equal to €28.54 is calculated from Equation 18 where $P^* = F$. In addition, the values of F for the finite case lie between €0 / MWh and €38.35 / MWh. Note that the value of F equal to €38.35 is calculated from Equation 30, where both branches of the threshold meet. Another important observation is that Equation 30 converges to Equation 18 as $T \to +\infty$, whereby the finite trigger converges to the perpetual trigger.

Second, the region below the dashed line depicts a market condition where the market price is below the price floor (i.e., $P < F$). In the finite case, the threshold values only exist for price floors between €38.35 / MWh, from Equation 30, and €54.09 / MWh, from Equation 31. Recall from Section 3.2 that values of F above €54.09 / MWh generate a positive NPV and a condition for an immediate investment. Policymakers that set the value of F within this interval give an investor a waiting option and a revenue from the guarantee when the project starts.

Table 2 presents the intervals of F, when $P < F$, for different values of the duration of the finite guarantee. We calculate F_{min} with Equation 30 and F_{max} with Equation 31. We observe that the size of the intervals decreases as the duration increases. In fact, an interesting observation is that Equation 30 converges to Equation 31 as $T \to +\infty$. In addition, Equation 31 converges to Equation 18 as $T \to +\infty$, which also helps to understand why the perpetual guarantee does not have investment threshold values for $P < F$.

For the region below the dashed line, when $P < F$, note that the threshold of the perpetual guarantee is inexistent for price floors greater than €28.54 / MWh (from Equation 30), because this policy scheme only induces investment for price floors greater than €28.54 with a risk-free profit (i.e., a positive NPV), as shown in Section 3.1. Consequently, investors do not have a waiting option for price floors greater than €28.54, which is not economically sound from a policymaking perspective.

Table 2: Intervals of the price floor for different values of the duration (T) of the finite guarantee, when the market price is below the price floor

	10 years	15 years	20 years	25 years	30 years
F_{min} (€ / MWh)	41.54	28.54	36.01	34.27	32.97
F_{max} (€ / MWh)	72.53	38.35	45.15	40.00	36.74

In Figure 2, we see that a higher duration of the guarantee induces an earlier investment. As expected, the threshold of the finite duration converges to the perpetual case as T increases. In Appendix G, we prove analytically that the derivative of the optimal threshold with respect to T is negative. In Figure 3, a higher volatility defers investment for both cases[2].

4 FIT Under Regulatory Uncertainty

Regulatory uncertainty has become an issue for renewable energy projects because governments have been changing their support schemes in the past years. Ritzenhofen & Spinler (2016) state

[2]Pindyck (1988) states in page 977 that the value of the option and the optimal investment threshold increase as σ increases, but the work does not present an analytical proof for this statement. In page 192 of the book from Dixit & Pindyck (1994), the authors also state that $\frac{\partial P^*}{\partial \sigma} > 0$, but do not present any analytical proof. We numerically tested $\frac{\partial P^*}{\partial \sigma}$ with all economically reasonable parameters and reached the conclusion that $\frac{\partial P^*}{\partial \sigma} > 0$.

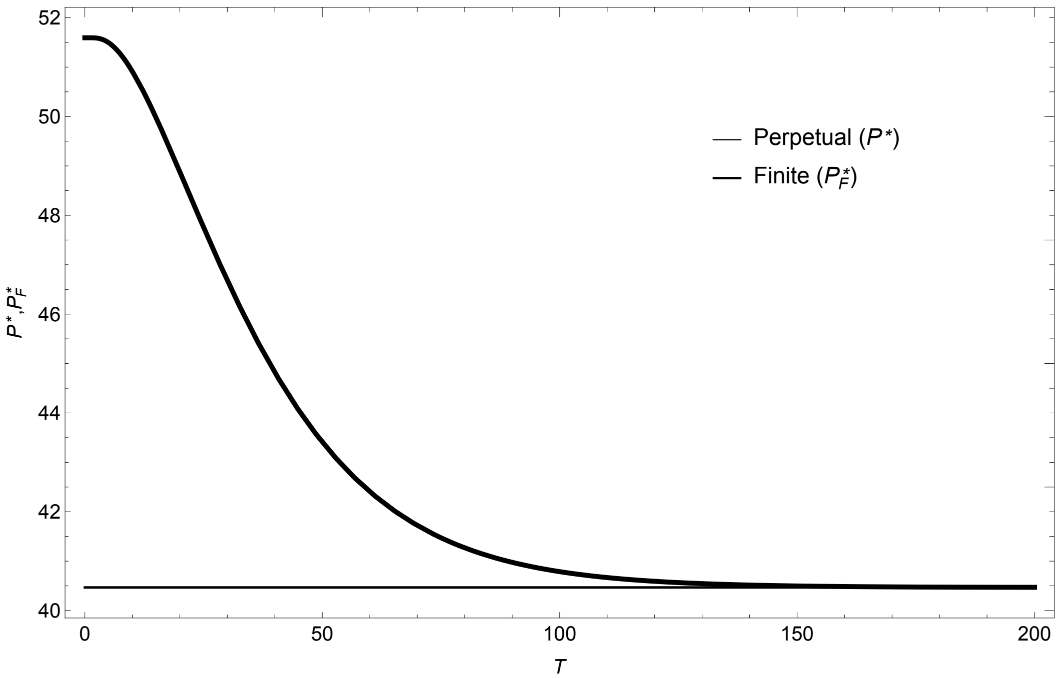

Figure 2: Investment thresholds as a function of time (T)

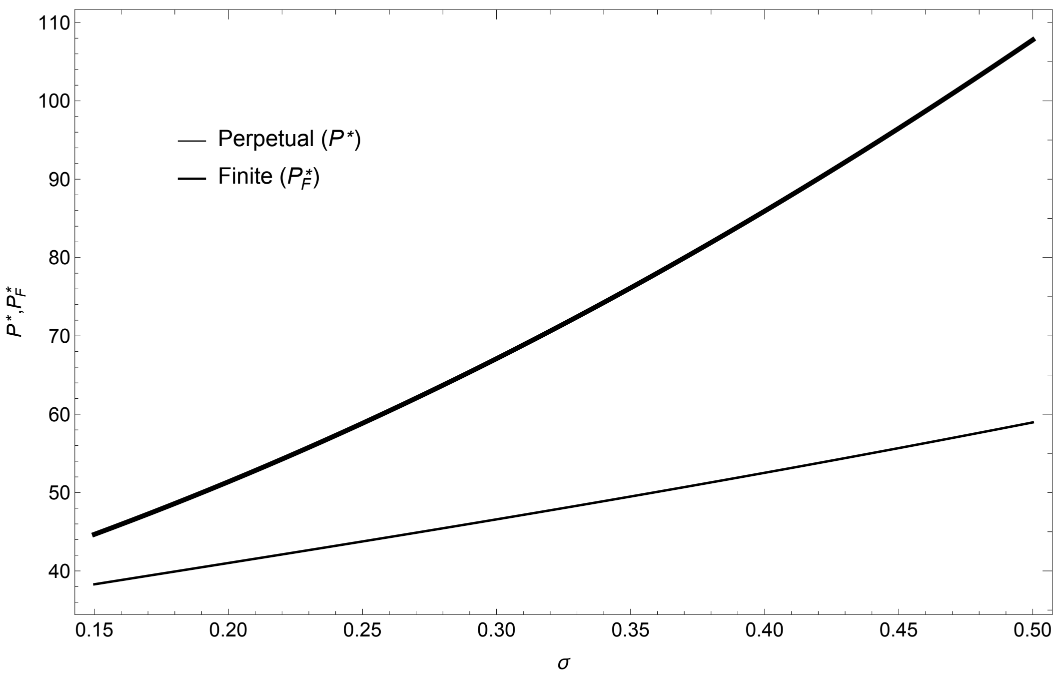

Figure 3: Investment thresholds as a function of the volatility (σ)

that governments revisit their policies in order to adjust the schemes to various factors, such as technology cost and budget constraints. However, policy revisions may have an impact on the investment decision. For instance, in the UK, investment projects have been put on hold due to government cuts to renewable energy subsidies (Megaw 2015).

In the following sections, we extend Section 3 and add a regulatory uncertainty into the FIT models with a minimum price guarantee, namely the perpetual and finite guarantee. In particular, we use a Poisson process in order to model occasional changes to the price floor before the project starts. In other words, the price floor may change while an investor is waiting for favorable market conditions. After the market price is equal to the optimal investment threshold, the investor signs a contract with a fixed price floor.

4.1 Perpetual Guarantee

In this section, we model a FIT with a perpetual guarantee that can be affected by a policy change (also known as a jump event) on the price floor before the project starts. In particular, we follow Itô's Lemma and include a Poisson process which leads to the following ODE:

$$\mu\, P\frac{\partial F_R(P,F)}{\partial P} + 0.5\sigma^2\, P^2\, \frac{\partial^2 F_R(P,F)}{\partial P^2} - rF_R(P,F) + \lambda[F(P,\omega F) - F_R(P,F)] = 0 \tag{32}$$

where λ denotes the mean arrival rate of a jump event during a time interval dt. Note that F and P are uncorrelated. In addition, the probability of occurring a jump event is λdt. The parameter ω is defined within the interval $[0, 1]$, whereby the price floor changes to ωF if the jump event occurs. The value of the option with regulatory uncertainty is $F_R(P, F)$. In addition, $F(P, \omega F)$ is the value of the option when the price floor is ωF, which is equal to Equation 33. Note that Equation 33 is equal to Equation 15 where we substitute ωF for F.

$$F(P,\omega F) = \begin{cases} C_1(\omega F)P^{\beta_1} & \text{for } P < P^*(\omega F) \\ \\ V(P,\omega F) - I & \text{for } P \geqslant P^*(\omega F) \end{cases} \tag{33}$$

where

$$C_1(\omega F) = (V(P^*(\omega F),\omega F) - I)\left(\frac{1}{P^*(\omega F)}\right)^{\beta_1} \tag{34}$$

$P^*(\omega F)$ is the solution for Equation 35, which is the same as Equation 16 where we substitute ωF for F:

$$(\beta_1 - \beta_2)[B_2(\omega F)][P^*(\omega F)]^{\beta_2} + (\beta_1 - 1)\frac{P^*(\omega F)}{r-\mu} - \beta_1 I = 0 \tag{35}$$

$B_2(\omega F)$ is Equation 10 where we substitute ωF for F:

$$B_2(\omega F) = \frac{(\omega F)^{1-\beta_2}}{\beta_1 - \beta_2}\left(\frac{\beta_1}{r} - \frac{\beta_1 - 1}{r-\mu}\right) \tag{36}$$

And $V(P^*(\omega F), \omega F)$ (i.e., the value of the project when the price floor is ωF) is the same as Equation 8 where we substitute ωF for F:

$$V(P^*(\omega F),\omega F) = B_2(\omega F)[P^*(\omega F)]^{\beta_2} + \frac{P^*(\omega F)}{r-\mu} \tag{37}$$

It is straightforward to see that $P^*(F) < P^*(\omega F)$ because the values of ω are within the interval $[0, 1]$ and hence $\omega F < F$ [3]. In other words, if investors are still waiting to invest when the price floor is F then they are certainly waiting to invest when the price floor is ωF, because lower price floor is equal to a higher threshold. Consequently, if an investor is willing to invest in a project with a price floor of ωF, an investment where the price floor is equal to F is even more attractive. Hence, the second branch (i.e., $P \geqslant P^*(\omega F)$) never occurs.

Substituting $C_1(\omega F)P^{\beta_1}$ for $F(P, \omega F)$ into the ODE (i.e., Equation 32) yields:

$$\mu\, P\frac{\partial F_R(P,F)}{\partial P} + 0.5\sigma^2\, P^2\, \frac{\partial^2 F_R(P,F)}{\partial P^2} - rF_R(P,F) + \lambda[C_1(\omega F)P^{\beta_1} - F_R(P,F)] = 0 \tag{38}$$

[3] In Figure 1, we can see that the investment threshold curve is a decreasing curve, thus $P^*(F) < P^*(\omega F)$ when the values of ω are within the interval $[0, 1]$

The solution to the ODE (Equation 38) is:

$$F_R(P,F) = E_1 P^{\eta_1} + C_1(\omega F)P^{\beta_1} \tag{39}$$

where η_1 is the positive root to the following quadratic equation:

$$0.5\sigma^2\eta(\eta-1) + \mu\eta - (r+\lambda) = 0 \tag{40}$$

Hence,

$$\eta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \left(\left(-\frac{1}{2} + \frac{\mu}{\sigma^2}\right)^2 + \frac{2(r+\lambda)}{\sigma^2}\right)^{\frac{1}{2}} \tag{41}$$

The value-matching and the smooth-pasting conditions are:

$$E_1 P_R^{*\eta_1} + C_1(\omega F)P_R^{*\beta_1} = V(P_R^*, F) - I \tag{42}$$

$$\eta_1 E_1 P_R^{*\eta_1} + \beta_1 C_1(\omega F)P_R^{*\beta_1} = \frac{\partial V(P_R^*, F)}{\partial P} P_R^* \tag{43}$$

where the value of the project is:

$$V(P_R^*, F) = \begin{cases} A_1 P_R^{*\beta_1} + \dfrac{F}{r} & \text{for } P_R^* < F \\ \\ B_2 P_R^{*\beta_2} + \dfrac{P_R^*}{r-\mu} & \text{for } P_R^* \geqslant F \end{cases} \tag{44}$$

From Equation 42, we find that E_1 is equal to $\dfrac{V(P_R^*, F) - I - C_1(\omega F)P_R^{*\beta_1}}{P_R^{*\eta_1}}$. Thus, substituting E_1 in Equation 39 yields:

$$F_R(P,F) = \begin{cases} \left(V(P_R^*, F) - I - C_1(\omega F)P_R^{*\beta_1}\right)\left(\dfrac{P}{P_R^*}\right)^{\eta_1} + C_1(\omega F)P^{\beta_1} & \text{for } P < P_R^* \\ \\ V(P,F) - I & \text{for } P \geqslant P_R^* \end{cases} \tag{45}$$

In addition, Equations 42 and 43 reduce to the following equation:

$$\eta_1(V(P_R^*, F) - I) + (\beta_1 - \eta_1)C_1(\omega F)P_R^{*\beta_1} = \frac{\partial V(P_R^*, F)}{\partial P} P_R^* \tag{46}$$

For $P_R^* < F$, the value-matching and the smooth-pasting conditions reduce to the following equation:

$$(\eta_1 - \beta_1)(A_1 - C_1(\omega F))P_R^{*\beta_1} + \eta_1\left(\frac{F}{r} - I\right) = 0 \tag{47}$$

Hence, the investment threshold is:

$$P_R^* = \left(\frac{-\eta_1}{(\eta_1 - \beta_1)(C_1(\omega F) - A_1)}\left(\frac{F}{r} - I\right)\right)^{\dfrac{1}{\beta_1}} \tag{48}$$

From Equation 48, we show that the value-matching and smooth-pasting conditions are not met for $P_R^* < F$, because $(C_1(\omega F) - A_1) < 0$ [4]. Hence, investment never occurs in this region,

[4]Proof is presented in Appendix D.

except when $\frac{F}{r} > I$, for which investment occurs immediately and generates a risk-free payoff (i.e., a positive NPV for every P).

For $P_R^* \geqslant F$, the value-matching and the smooth-pasting conditions reduce to the following equation that must be solved numerically to find the investment threshold P_R^*:

$$(\eta_1 - \beta_2) B_2 {P_R^*}^{\beta_2} - (\eta_1 - \beta_1) C_1(\omega F) {P_R^*}^{\beta_1} + (\eta_1 - 1)\frac{P_R^*}{r-\mu} - \eta_1 I = 0 \tag{49}$$

In Appendix E, we prove that the value of the option and investment threshold with and without regulatory uncertainty are the same when $\lambda \to 0$. This result can be explained through parameter λ, because the average time difference between two consecutive jump events is equal to $1/\lambda$. Thus, the jump event never occurs when $\lambda \to 0$. The same result holds when $\omega = 1$ (i.e., $\omega F = F$), because the price floor never changes even when jump events occur.

In addition, as the average time difference between two consecutive jump events goes to 0 (i.e., $\lambda \to +\infty$), the value of the option and investment threshold reduce to the results with no regulatory uncertainty where the price floor is equal to ωF, instead of F.

4.2 Finite Guarantee

In this section, we model a FIT with a finite guarantee that can be affected by a policy change on the price floor before the project starts. Applying Itô's Lemma leads to the following ODE:

$$\mu\, P \frac{\partial F_{FR}(P,F)}{\partial P} + 0.5\sigma^2\, P^2\, \frac{\partial^2 F_{FR}(P,F)}{\partial P^2} - rF_{FR}(P,F) + \lambda[F_F(P,\omega F) - F_{FR}(P,F)] = 0 \tag{50}$$

where $F_{FR}(P,F)$ is the value of option with regulatory uncertainty and $F_F(P,\omega F)$ is the value of the option when the price floor is ωF. $F_F(P,\omega F)$ (i.e., Equation 51) is equal to Equation 25 where we substitute ωF for F.

$$F_F(P,\omega F) = \begin{cases} D_1(\omega F) P^{\beta_1} & \text{for } P < P_F^*(\omega F) \\ \\ V_F(P,\omega F) - I & \text{for } P \geqslant P_F^*(\omega F) \end{cases} \tag{51}$$

where

$$D_1(\omega F) = (V_F(P_F^*(\omega F),\omega F) - I)\left(\frac{1}{P_F^*(\omega F)}\right)^{\beta_1} \tag{52}$$

Following the same steps as in the previous section, in order to find the investment threshold $P_F^*(\omega F)$, we substitute ωF for F in Equation 26.

And, we calculate the value of the project $V_F(P^*(\omega F),\omega F)$, by substituting ωF for F in Equation 21.

Similar to the perpetual case, we also know that $P_F^*(F) < P_F^*(\omega F)$ because the values of ω are within the interval $[0,1]$ and $\omega F < F$. Hence, the second branch (i.e $P \geqslant P_F^*(\omega F)$) never occurs. Substituting the value of the option when the price floor is ωF (i.e., $F_F(P,\omega F) = D_1(\omega F)P^{\beta_1}$) into the ODE (i.e., Equation 50) yields:

$$\mu\, P \frac{\partial F_{FR}(P,F)}{\partial P} + 0.5\sigma^2\, P^2\, \frac{\partial^2 F_{FR}(P,F)}{\partial P^2} - rF_{FR}(P,F) + \lambda[D_1(\omega F)P^{\beta_1} - F_{FR}(P,F)] = 0 \tag{53}$$

The general solution to this ODE is given by:

$$F_{FR}(P,F) = G_1 P^{\eta_1} + D_1(\omega F)P^{\beta_1} \tag{54}$$

Following the same steps as in the previous sections, the value of the option is:

$$F_{FR}(P,F)=\begin{cases}(V_F(P^*_{FR},F)-I-D_1(\omega F)P^{*\beta_1}_{FR})\left(\dfrac{P}{P^*_{FR}}\right)^{\eta_1}+D_1(\omega F)P^{\beta_1} & \text{for } P<P^*_{FR}\\ \\ V_F(P,F)-I & \text{for } P\geqslant P^*_{FR}\end{cases} \tag{55}$$

And, the investment threshold is the solution of the followings equations that must be solved numerically:

$$\begin{cases}(\eta_1-\beta_1)(A_1N(d_{\beta_1})-D_1(\omega F))P^{*\beta_1}_{FR}-(\eta_1-\beta_2)B_2P^{*\beta_2}_{FR}N(d_{\beta_2})\\ +\eta_1\left(\dfrac{F}{r}-\dfrac{F}{r}e^{-rT}(1-N(d_0))-I\right)\\ +(\eta_1-1)\dfrac{P^*_{FR}}{r-\mu}e^{-(r-\mu)T}(1-N(d_1))=0 & \text{for } P^*_{FR}<F\\ \\ -(\eta_1-\beta_1)(A_1(1-N(d_{\beta_1}))+D_1(\omega F))P^{*\beta_1}_{FR}+(\eta_1-\beta_2)B_2P^{*\beta_2}_{FR}(1-N(d_{\beta_2}))\\ +(\eta_1-1)\dfrac{P^*_{FR}}{r-\mu}(1-e^{-(r-\mu)T}N(d_1)\\ +e^{-(r-\mu)T})-\eta_1\left(\dfrac{F}{r}e^{-rT}(1-N(d_0))+I\right)=0 & \text{for } P^*_{FR}\geqslant F\end{cases} \tag{56}$$

Following the same steps in Section 3.2, we can find the value of F that both branches in Equation 56 yield the same value of P^*_{FR}. The following nonlinear equation must be solved numerically in order to find this value of F:

$$\begin{aligned}&D_1(\omega F))F^{\beta_1}+(\eta_1-\beta_2)B_2(1-N(d_{\beta_2(P^*_{FR}=F)}))F^{\beta_2}\\ &\quad+\left(\frac{\eta_1-1}{r-\mu}\left(1-e^{-(r-\mu)T}N(d_{1(P^*_{FR}=F)})+e^{-(r-\mu)T}\right)-\frac{\eta_1e^{-rT}}{r}(1-N(d_{0(P^*_{FR}=F)})\right)F\\ &\qquad-(\eta_1-\beta_1)(A_1(1-N(d_{\beta_1(P^*_{FR}=F)}))-\eta_1I=0\end{aligned} \tag{57}$$

Where $d_\beta(P^*_{FR}=F)$ is equal to:

$$d_\beta(P^*_{FR}=F)=\frac{\left(\mu+\sigma^2\left(\beta-\dfrac{1}{2}\right)\right)T}{\sigma\sqrt{T}} \tag{58}$$

In addition, we prove in Appendix F that the value of the option $F_{FR}(P,F)$ and investment threshold P^*_{FR} reduce to the equations without regulatory uncertainty when $\lambda\to 0$ (i.e., the event never occurs) or $\omega=1$ (i.e., the price floor never changes). In addition, when $\lambda\to+\infty$ (i.e., the event certainly occurs), the value of the option $F_{FR}(P,F)$ and investment threshold P^*_{FR} reduce to equations with no regulatory uncertainty where the price floor is ωF, instead of F.

4.3 Numerical Analysis

This section presents an analysis of the investment thresholds and the influence of a regulatory uncertainty on a renewable energy project. In particular, we analyze the investment thresholds by changing: (i) the mean arrival rate of the jump event λ, (ii) the parameter ω that changes the price floor to ωF if the jump event occurs, and (iii) the volatility σ. For the analysis, we use the same base-case parameters in Table 1 together with $\omega = 0.8$ and $\lambda = 0.5$.

The jump event can be consider as an unexpected[5] reduction due to a regulator's decision. For instance, the Switzerland Federal Authorities reduced in 2015 the solar FIT payments (Woods 2014) as following: 12% reduction for installations over 1MW, 18% for installations between 30kW - 1MW, and a 23% reduction for installations under 30kW.

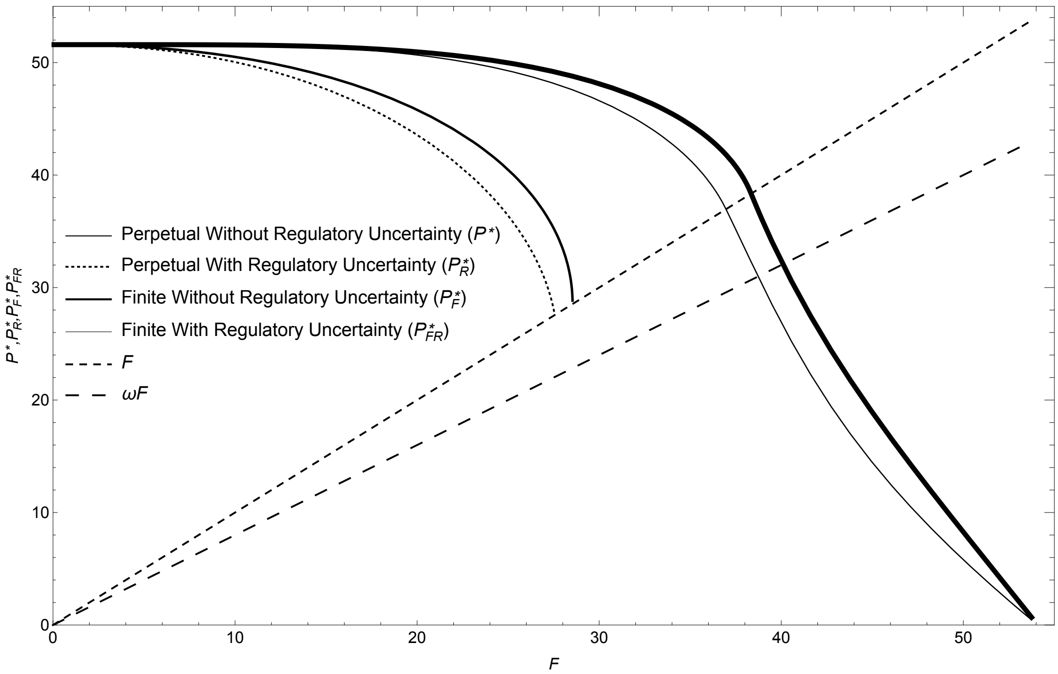

Figure 4: Optimal investment threshold for a perpetual and finite guarantee with and without regulatory uncertainty as a function of F

Figure 4 presents the value of the investment thresholds for a finite guarantee and for a perpetual guarantee with and without regulatory uncertainty as a function of the price floor F. We also include the value of ωF and the value of the price floor F. Recall that the perpetual guarantee only induces investment for $P < F$ when $F \geqslant rI$ and consequently generates a positive NPV for any P (i.e., a risk-free profit). A finite guarantee is able to induce investment for market prices below F without producing a risk-free profit. The investment threshold for the finite case is higher than the perpetual case within a scenario with regulatory uncertainty and also without regulatory uncertainty. This is an expected result because investors have a guarantee for a shorter period of time in the finite case.

When comparing the perpetual thresholds with and without regulatory uncertainty, the investment threshold is lower when a regulatory uncertainty is present. The same results hold for the finite thresholds with and without regulatory uncertainty. Hence, regulatory uncertainty accelerates investment because investors are willing to invest earlier in order to guarantee a higher price floor.

In the finite case with regulatory uncertainty, we calculate the price floor where both branches of Equation 56 yield the same value of P^*_{FR}. From the base-case parameters, we find that price floors above €36.97 / MWh are recommended values for policymakers because they guarantee that investors start receiving the price floor instead of the market price when the project starts.

Figure 5 presents the investment thresholds as a function of the parameter ω. Recall that the price floor changes to ωF when a jump event occurs. We observe that the investment thresholds for the perpetual case P^*_R and the finite case P^*_{FR} decrease as we reduce ω. This is due to the

[5] We are not considering reductions based on a mechanism known as 'degression', where new registrants know in advance that tariffs are going to be reduced progressively.

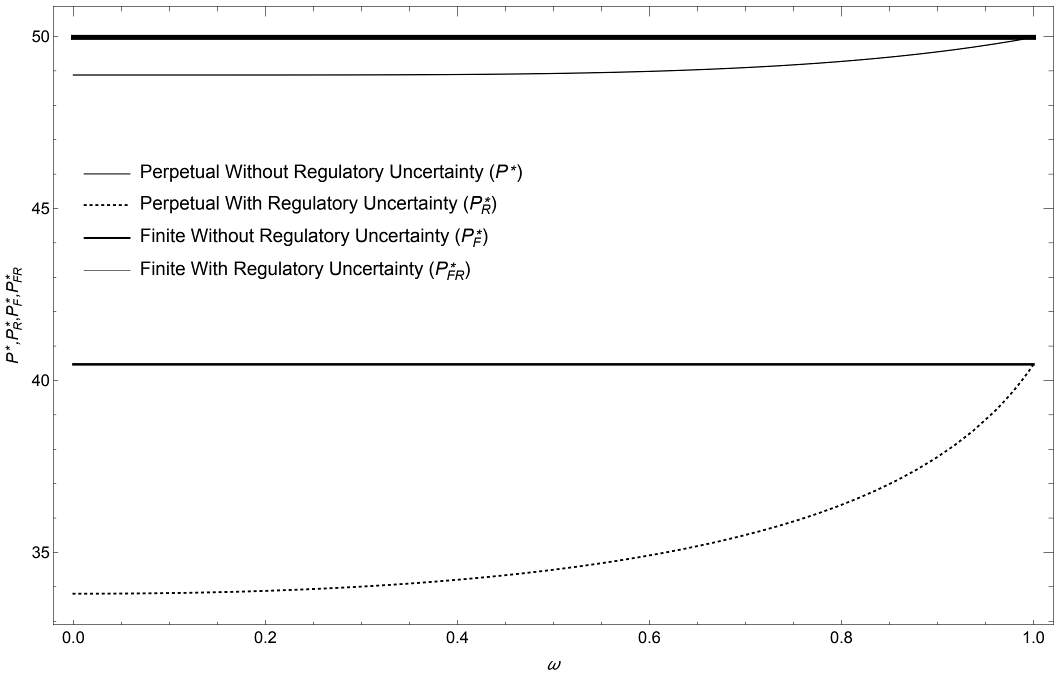

Figure 5: Optimal investment threshold for a perpetual and finite guarantee with and without regulatory uncertainty as a function of ω

fact that lower values of ω produce higher reductions in the price floor and consequently a lower expected profit. These potential losses lead to lower investment thresholds, because investors decide to accelerate investment in order to guarantee a higher price floor. When ω is equal to one (i.e., no reduction in the price floor), the thresholds with regulatory uncertainty meet the thresholds without regulatory uncertainty, within both the perpetual and finite cases[6]. Table 3 presents investment thresholds for some values of ω. For instance, an ω of 0.85 represents a reduction of 15% in the price floor, which leads to a reduction of 8.60% in the perpetual guarantee's threshold and 1.15% in the finite guarantee's threshold. We can observe from Table 3 and Figure 5 that the perpetual case leads to a higher reduction than the finite case, because the perpetual guarantee is more affected by ω due to the longer duration of the guarantee.

Table 3: Examples of reductions of the threshold for different values of ω

ω	% Reduction Price Floor	Perpetual Guarantee Threshold (€ / MWh)	% Reduction Threshold (Perpetual)	Finite Guarantee Threshold (€ / MWh)	% Reduction Threshold (Finite)
0.95	5.00%	38.35	5.23%	49.74	0.47%
0.90	10.00%	37.77	6.65%	49.55	0.84%
0.85	15.00%	36.99	8.60%	49.40	1.15%
0.80	20.00%	36.38	10.10%	49.28	1.40%
0.75	25.00%	35.90	11.29%	49.18	1.60%

Figure 6 presents the investment thresholds for different values of the parameter λ of the Poisson process. Recall that the probability of occurring a jump event is λdt. In Figure 6, we see that the threshold decreases as the lambda increases, for both the perpetual and finite cases. This is due to the fact that higher values of λ increase the probability of occurring a reduction in the price floor before the project starts. Consequently, investors accelerate investment in order to

[6] Appendix E and Appendix F also reach the same conclusion with an analytical approach

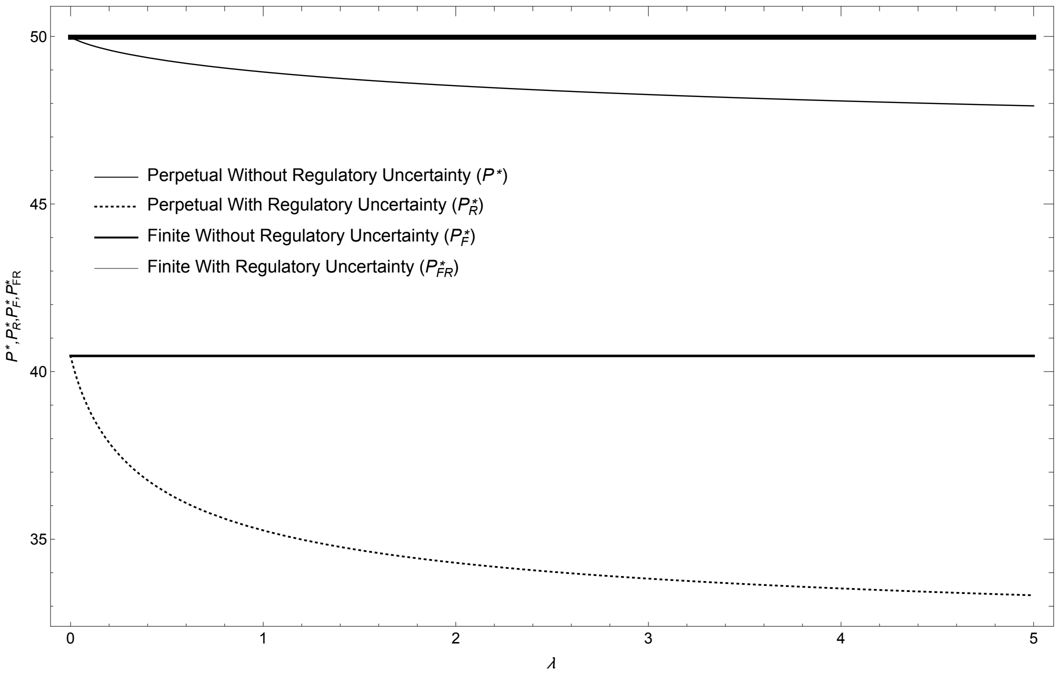

Figure 6: Optimal investment threshold for a perpetual and finite guarantee with and without regulatory uncertainty as a function of λ

guarantee a higher price floor. Table 4 presents the reduction of the thresholds for the perpetual and finite cases for different values of λ. We also calculate the expected time to occur a reduction, which is equal to $1/\lambda$. For instance, a λ equal to 0.5 has an expected time to occur the reduction of 2 years, which leads to a reduction of 10.10% in the perpetual guarantee's threshold and a reduction of 1.40% in the finite guarantee's threshold. We also observe a higher reduction in the perpetual case than the finite case, because the perpetual guarantee has a longer duration.

Table 4: Examples of reductions of the threshold for different values of λ

λ	Expected Time To Occur Reduction (years)	Perpetual Guarantee Threshold (€ / MWh)	% Reduction Threshold (Perpetual)	Finite Guarantee Threshold (€ / MWh)	% Reduction Threshold (Finite)
0.1	10	38.82	4.07%	49.75	0.46%
0.2	5	37.88	6.40%	49.59	0.77%
0.5	2	36.38	10.10%	49.28	1.40%
1.0	1	35.26	12.87%	48.94	2.07%
2.0	0.5	34.29	15.25%	48.53	2.90%

Figure 7 depicts the investment thresholds as a function of the volatility σ. The results of the thresholds with regulatory uncertainty follow the same pattern as the thresholds without regulatory uncertainty, for both the perpetual and finite cases. In summary, market uncertainty defers investment for all cases.

In Figures 4, 5, and 6, note that the gap between the investment thresholds with and without regulatory uncertainty for the perpetual case is always greater than the gap for the finite case. This finding in the perpetual guarantee is due to the duration of the guarantee. In other words, the regulatory uncertainty has a higher impact on a perpetual guarantee because an investor has a guarantee for a longer period of time. Thus, investors accelerate the investment decision to avoid the reduction. Also, the investment thresholds of a finite guarantee are always greater than the investment thresholds of a perpetual guarantee, which is consistent with the findings in Section

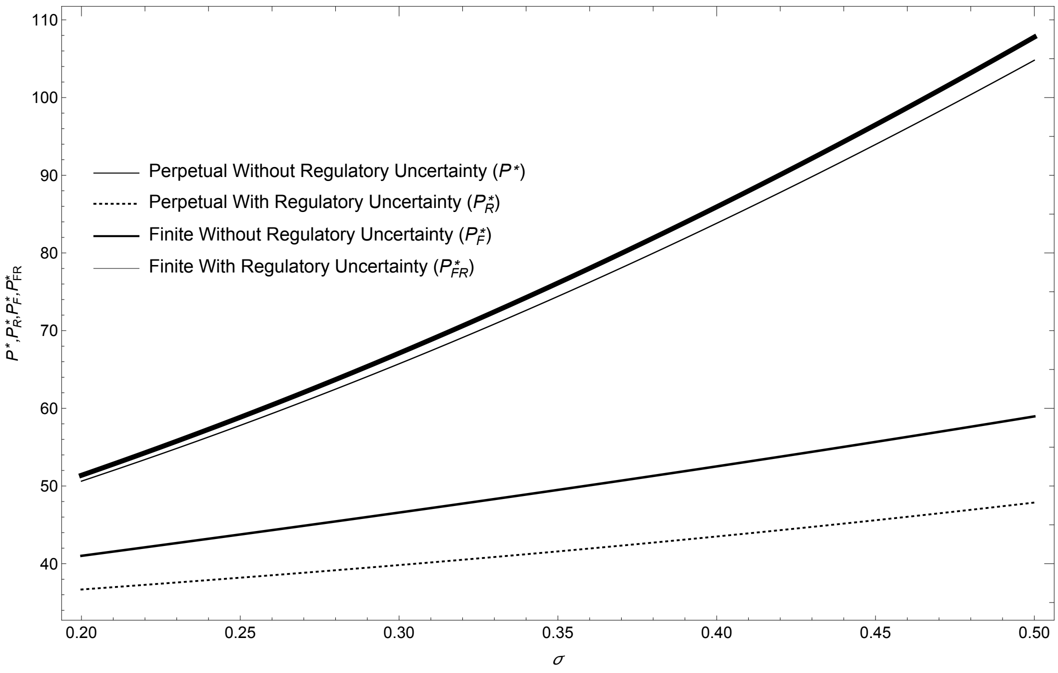

Figure 7: Optimal investment threshold for a perpetual and finite guarantee with and without regulatory uncertainty as a function of σ

3.3.

5 Concluding Remarks

This work analyzes renewable energy investments with a FIT that includes a minimum price guarantee in two different scenarios, namely a perpetual guarantee and a finite guarantee. For each scenario, we derive a real options model in order to calculate the value of the project, the option value and the optimal investment threshold. In particular, we use an analytical real options framework with the following embedded options: (i) a waiting option, where the investor may wait to deploy the project when the market is favorable, and (ii) put options, where the investor has a set of options to sell the energy for a fixed price (i.e., the price floor) when the market price is below the price floor.

An interesting finding of our model is that the perpetual guarantee is not economically sound because it can only induce investment for prices below the price floor when offering a risk-free investment opportunity. In other words, investment only occurs for market prices below the price floor when the revenue from the guarantee is higher than the investment cost. This apparent counter-intuitive result is due to the perpetual guarantee, which is not foregone if investment does not occur. Within the finite scenario, the support scheme induces an earlier investment when either the duration of the guarantee or price floor increases.

We then extend the models for the perpetual and finite guarantees in order to include regulatory uncertainty. In particular, we model the regulatory uncertainty as an occasional reduction on the price floor with a Poisson process. With these models, we calculate the value of the project, the option value and the optimal investment threshold. We find two interesting results. First, the scenario with a perpetual guarantee continues to induce investment for prices below the price floor when offering a risk-free investment (i.e., an investment that has a positive NPV). Second, investment thresholds decrease with either a greater reduction in the price floor or higher probability of occurring the reduction. These findings are due to the fact that investors prefer to accelerate investment in order to guarantee a higher investment threshold. In all cases, market uncertainty defers investment.

From a policymaking perspective, the model provides interesting insights to FIT design with a minimum price guarantee. In particular, the definition of the value of the price floor is a key challenge for policymakers, whereby the scheme should provide a secure investment while creating an incentive for investors to produce energy when demand is high. In this paper, we shed some light on how to define the value of the price floor. An interesting interval for the price floor is when the tariff induces investment for market prices below the price floor, because an investor starts the project with a revenue from the guarantee and thus provides a secure investment condition. Should the market price increase above the price floor, an investor will have an incentive to produce more energy and thus increase its revenue. In Section 3.2 and Section 3.3, our work shows how to calculate the price floor interval where the investment trigger is below the price floor for the finite case. Recall that the perpetual case only induces investment with a risk-free profit when the market price is below the price floor, which is not a desired condition to be offered from a feed-in tariff.

Regarding the duration of the finite guarantee, our findings show that the size of the interval for the price floor decreases as the duration increases, when the market price is below the price floor. Policymakers have a trade-off to consider. Shorter durations of the guarantee have larger intervals of the price floor but also have higher investment threshold values. In contrast, longer durations of the guarantee have smaller intervals of the price floor but have lower investment threshold values.

When regulatory uncertainty is included in the analysis, the findings have three important implications for policymakers. First, if the expected time to occur a reduction decreases then the investment threshold also decreases. In other words, policymakers that reduce the price floor more frequently are creating conditions for investors to accelerate investment in order to guarantee a higher price floor. Second, greater reductions in the price floor also lead to lower investment thresholds. Hence, policymakers that apply greater reductions in the price floor are also creating conditions for investors to accelerate investment. Third, as energy markets become more volatile, the investment trigger increases. Hence, investors are expected to postpone the investment decision. In fact, the third implication applies to a scenario with and without regulatory uncertainty.

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Appendix A Value of the Project with a Finite Guarantee

Building on the work from Shackleton & Wojakowski (2007), we derive a model for a renewable energy project that has a FIT with a finite guarantee. As demonstrated in Equation 8[7], the value of the project with a perpetual guarantee is:

$$V(P,F,+\infty) = \begin{cases} A_1 P^{\beta_1} + \dfrac{F}{r} & \text{for } P < F \\ \\ B_2 P^{\beta_2} + \dfrac{P}{r-\mu} & \text{for } P \geqslant F \end{cases} \tag{A.1}$$

Now, the value of the project is extended for a finite guarantee. The value of the project in Equation A.2 is expressed as the difference between the values of a project with a perpetual guarantee $V(P,F,+\infty)$ and with a delayed perpetual guarantee $V(P_T,F,+\infty)$ that starts at time T. Hence, the value of the project until time T[8] (i.e., during the validity of the FIT contract) is:

$$V_G(P,T) = V(P,F,+\infty) - V(P_T,F,+\infty) = V(P,F,+\infty) - e^{-rT}E_0^Q\left[V(P_T,F,+\infty)\right] \tag{A.2}$$

We now derive the values of $V(P,F,+\infty)$ and $V(P_T,F,+\infty)$. Rewriting Equation A.1 yields:

$$V(P,F,+\infty) = \left[A_1 P^{\beta_1} + \frac{F}{r}\right]\mathbb{1}_{P<F} + \left[B_2 P^{\beta_2} + \frac{P}{r-\mu}\right]\mathbb{1}_{P\geqslant F} \tag{A.3}$$

where $\mathbb{1}$ is an indicator function taking values one when the specified event occurs and zero otherwise. In addition, the value of a project with a perpetual guarantee that starts at time T is:

$$V(P_T,F,+\infty) = \left[A_1 P_T^{\beta_1} + \frac{F}{r}\right]\mathbb{1}_{P_T<F} + \left[B_2 P_T^{\beta_2} + \frac{P_T}{r-\mu}\right]\mathbb{1}_{P_T\geqslant F} \tag{A.4}$$

We then calculate the expected value of the four components in $V(P_T,F,+\infty)$, namely $A_1 P_T^{\beta_1}$, $\frac{F}{r}$, $B_2 P_T^{\beta_2}$, and $\frac{P_T}{r-\mu}$, because of Equation A.2. Following Shackleton & Wojakowski (2007), the general formulas to calculate each component are:

$$e^{-rT}E_0^Q\left[P_T^{\beta}1_{P_T<F}\right] = e^{q(\beta)T}P^{\beta}N(-d_\beta) \tag{A.5}$$

$$e^{-rT}E_0^Q\left[P_T^{\beta}1_{P_T\geqslant F}\right] = e^{q(\beta)T}P^{\beta}N(d_\beta) \tag{A.6}$$

where $q(\beta)$ is defined below:

$$q(\beta) = \frac{1}{2}\sigma^2\beta(\beta-1) + \beta\mu - r \tag{A.7}$$

We can interpret β as an elasticity. Recall that β_1 and β_2 are the solutions of the quadratic equation above (i.e., $q(\beta)=0$). In addition, $\beta_1 > 1$ and $\beta_2 < 0$. There are also two more values of β associated with the value of the project, namely $\beta = 0$ and $\beta = 1$.

[7] Note that we use a different notation in Equation A.1 for the value of the project, but $V(P,F)$ in Equation 8 is the same as $V(P,F,+\infty)$

[8] Also note that we use a different notation in Equation A.2 for the value of the project during the validity of the FIT contract, but $V_T(P,F)$ in Equation 19 is the same as $V_G(P,T)$

The cumulative probability distribution function for a standardized normal distribution is defined by the function $N(d_\beta)$. In other words, we can interpret the function $N(d_\beta)$ as a probability that a variable with a standard normal distribution will be less than d_β. Also, d_β is defined as:

$$d_\beta = \frac{\ln \frac{P}{F} + \left(\mu + \sigma^2 \left(\beta - \frac{1}{2}\right)\right) T}{\sigma\sqrt{T}} \tag{A.8}$$

where $\beta_1, \beta_2, 0$ and 1 can substitute β.

The expected value of the components in $V(P_T, F, +\infty)$ having elasticity β_1 with respect to P_T is:

$$q(\beta_1) = 0 \tag{A.9}$$

$$e^{-rT} E_0^Q \left[A_1 P^{\beta_1}\right] = A_1 P^{\beta_1} N(-d_{\beta_1}) \tag{A.10}$$

And the expected value of the components in $V(P_T, F, +\infty)$ having elasticity $\beta = 0$ with respect to P_T is:

$$q(0) = -r \tag{A.11}$$

$$e^{-rT} E_0^Q \left[\frac{F}{r}\right] = e^{-rT} \frac{F}{r} N(-d_0) \tag{A.12}$$

And the expected value of the components in $V(P_T, F, +\infty)$ having elasticity β_2 with respect to P_T is:

$$q(\beta_2) = 0 \tag{A.13}$$

$$e^{-rT} E_0^Q \left[B_2 P^{\beta_2}\right] = B_2 P^{\beta_2} N(d_{\beta_2}) \tag{A.14}$$

And the expected value of the components in $V(P_T, F, +\infty)$ having elasticity $\beta = 1$ with respect to P_T is:

$$q(1) = \mu - r \tag{A.15}$$

$$e^{-rT} E_0^Q \left[\frac{P}{r-\mu}\right] = \frac{P}{r-\mu} N(d_1) e^{-(r-\mu)T} \tag{A.16}$$

Recall that $V_G(P,T) = V(P, F, +\infty) - e^{-rT} E_0^Q [V(P_T, F, +\infty)]$ (i.e., Equation A.2). Substituting Equations A.1, A.10, A.12, A.14 and A.16 into Equation A.2 yields the value of the project for $P < F$:

$$\begin{aligned} V_G(P,T) = A_1 P^{\beta_1} + \frac{F}{r} - [A_1 P^{\beta_1} N(-d_{\beta_1}) + \frac{F}{r} e^{-rT} N(-d_0) \\ + B_2 P^{\beta_2} N(d_{\beta_2}) + \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1)] \text{ for } P < F \end{aligned} \tag{A.17}$$

As $N(-d_\beta) = 1 - N(d_\beta)$, we rewrite the value of the project $V_G(P,T)$ for $P < F$ as following:

$$V_G(P,T) = A_1 P^{\beta_1} N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0)))$$
$$- B_2 P^{\beta_2} N(d_{\beta_2}) - \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1) \text{ for } P < F \quad \text{(A.18)}$$

We now calculate the value of the project $V_G(P,T)$ for $P \geqslant F$. Substituting Equations A.1, A.10, A.12, A.14 and A.16 into Equation A.2 yields:

$$V_G(P,T) = B_2 P^{\beta_2} + \frac{P}{r-\mu} - [A_1 P^{\beta_1} N(-d_{\beta_1}) + \frac{F}{r} e^{-rT} N(-d_0)$$
$$+ B_2 P^{\beta_2} N(d_{\beta_2}) + \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1)] \text{ for } P \geqslant F$$
$$\text{(A.19)}$$

As $N(-d_\beta) = 1 - N(d_\beta)$, we rewrite Equation A.19 as:

$$V_G(P,T) = -A_1 P^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r} e^{-rT}(1 - N(d_0))$$
$$+ B_2 P^{\beta_2}(1 - N(d_{\beta_2})) + \frac{P}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) \text{ for } P \geqslant F$$
$$\text{(A.20)}$$

Hence, the value of the project is:

$$V_G(P,T) = \begin{cases} A_1 P^{\beta_1} N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ \quad -B_2 P^{\beta_2} N(d_{\beta_2}) - \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1) & \text{for } P < F \\ \\ -A_1 P^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r} e^{-rT}(1 - N(d_0)) \\ \quad +B_2 P^{\beta_2}(1 - N(d_{\beta_2})) \\ \quad +\frac{P}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) & \text{for } P \geqslant F \end{cases} \quad \text{(A.21)}$$

The value of the project $V_G(P,T)$ only considers the cash flow until time T, whereby the finite guarantee of the FIT contract is valid. However, the investor receives a cash flow after time T, namely $\frac{P}{r-\mu} e^{-(r-\mu)T}$, for selling the energy to the market. Hence, the value of the project for the periods before and after time T is the following:

$$V_F(P,F) = V_G(P,T) + \frac{P}{r-\mu} e^{-(r-\mu)T} \quad \text{(A.22)}$$

Appendix B Limits of the Value of a Project with a Finite Guarantee

This appendix calculates the limits of the value of the project with a finite guarantee (i.e., Equation A.22). We start with the limit when $T \to +\infty$. As Equation A.22 depends on d_0, d_1, d_{β_1} and d_{β_2}, we calculate the limit for each of these variables:

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

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

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

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

Recall that β_1 and β_2 are the solutions of Equation A.7, where $\beta_2 < 0$ and $\beta_1 > 1$. Note in Equation B.3 that $\mu + \sigma^2(\beta_1 - \frac{1}{2}))$ is always positive because $\beta_1 > 1$; thus $\lim_{T\to+\infty} d_{\beta_1} = +\infty$. Similarly, note in Equation B.4 that $(\mu + \sigma^2(\beta_2 - \frac{1}{2}))$ is always negative because $\beta_2 < 0$; hence $\lim_{T\to+\infty} d_{\beta_2}$ is always $-\infty$. As $N(+\infty) = 1$ and $N(-\infty) = 0$, then $N(d_{\beta_1}) = 1$ and $N(d_{\beta_2}) = 0$.

From Equation A.22, when $T \to +\infty$, we calculate the value of the project:

$$\lim_{T\to+\infty} \Bigg[A_1 P^{\beta_1} N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ -B_2 P^{\beta_2} N(d_{\beta_2}) - \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1) + \frac{P}{r-\mu} e^{-(r-\mu)T} \Bigg] = \\ = A_1 P^{\beta_1} + \frac{F}{r} \quad \text{for } P < F \tag{B.5}$$

$$\lim_{T\to+\infty} \Bigg[-A_1 P^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r} e^{-rT}(1 - N(-d_0)) \\ +B_2 P^{\beta_2}(1 - N(d_{\beta_2})) + \frac{P}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) + \frac{P}{r-\mu} e^{-(r-\mu)T} \Bigg] = \\ = B_2 P^{\beta_2} + \frac{P}{r-\mu} \quad \text{for } P \geqslant F \tag{B.6}$$

Therefore, we demonstrate that the value of the project with a finite guarantee is the same value as the perpetual guarantee (i.e., Equation 8) when $T \to +\infty$.

We then calculate the value of the project when $T \to 0$. Equation A.22 depends on d_0, d_1, d_{β_1} and d_{β_2}. In fact, the limits for all these variables are the same:

$$\lim_{T\to 0} d_{0,1,\beta_1,\beta_2} = \begin{cases} -\infty & \text{for } P < F \\ \\ +\infty & \text{for } P \geqslant F \end{cases} \tag{B.7}$$

From Equation A.22, we calculate the value of the project:

$$\begin{aligned} \lim_{T\to 0} \Bigg[& A_1 P^{\beta_1} N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\ & -B_2 P^{\beta_2} N(d_{\beta_2}) - \frac{P}{r-\mu} e^{-(r-\mu)T} N(d_1) + \frac{P}{r-\mu} e^{-(r-\mu)T} \Bigg] = \\ & = \frac{P}{r-\mu} \text{ for } P < F \end{aligned} \tag{B.8}$$

$$\begin{aligned} \lim_{T\to 0} \Bigg[& -A_1 P^{\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r} e^{-rT}(1 - N(-d_0)) \\ & +B_2 P^{\beta_2}(1 - N(d_{\beta_2})) + \frac{P}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) + \frac{P}{r-\mu} e^{-(r-\mu)T} \Bigg] = \\ & = \frac{P}{r-\mu} \text{ for } P \geqslant F \end{aligned} \tag{B.9}$$

Hence, we demonstrate for both limits above that the value of the project is equal to a cash flow without a guarantee. In other words, the NPV of a renewable energy project that sells energy to the market.

Appendix C Investment Threshold of the Project with a Finite Guarantee

This appendix presents the derivation of the investment threshold of a renewable energy project with a finite guarantee. Recall that the investment threshold satisfies the value-matching and smooth-pasting conditions. From the investor's perspective, the value-matching condition is the optimal investment point where the decision of holding the option or deploying the project is indifferent. The smooth-pasting condition is a requirement in which the value of the option needs to be tangent to the value of the project at the optimal investment point.

Appendix C.1 The Investment Threshold for the First Interval: $P < F$

For $P < F$, we calculate the value-matching condition in Equation C.1. Note that Equation C.1 represents the optimal investment point where the value of the option (i.e., $D_1 P_F^{*\beta_1}$) is equal to the value of the project (Equation A.22 for the interval $P < F$) minus the investment cost.

$$
\begin{aligned}
D_1 P_F^{*\beta_1} = A_1 P_F^{*\beta_1} N(d_{\beta_1}) + \frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) \\
- B_2 P_F^{*\beta_2} N(d_{\beta_2}) - \frac{P_F^*}{r-\mu} e^{-(r-\mu)T} N(d_1) + \frac{P_F^*}{r-\mu} e^{-(r-\mu)T} - I \quad \text{(C.1)}
\end{aligned}
$$

We also calculate the smooth-pasting condition in Equation C.2, where the slope of the value of the option is equal to the slope of the value of the project. Hence, we calculate the first derivatives of both sides of Equation C.1 with respect to P_F^*, which yields Equation C.2.

$$
\begin{aligned}
\beta_1 D_1 P_F^{*\beta_1 - 1} = A_1 P_F^{*\beta_1} \frac{\partial N(d_{\beta_1})}{\partial P_F^*} + \beta_1 A_1 P_F^{*\beta_1 - 1} N(d_{\beta_1}) + \frac{F}{r} e^{-rT} \frac{\partial N(d_0)}{\partial P_F^*} \\
- \beta_2 B_2 P_F^{*\beta_2 - 1} N(d_{\beta_2}) - B_2 P_F^{*\beta_2} \frac{\partial N(d_{\beta_2})}{\partial P_F^*} \\
- \frac{1}{r-\mu} e^{-(r-\mu)T} N(d_1) - \frac{P_F^*}{r-\mu} e^{-(r-\mu)T} \frac{\partial N(d_1)}{\partial P_F^*} \\
+ \frac{1}{r-\mu} e^{-(r-\mu)T} \quad \text{(C.2)}
\end{aligned}
$$

As in Shackleton & Wojakowski (2007), 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:

$$
\begin{aligned}
-(\beta_1 - \beta_2) B_2 P_F^{*\beta_2} N(d_{\beta_2}) - (\beta_1 - 1)\left(\frac{P_F^*}{r-\mu} e^{-(r-\mu)T} N(d_1)\right) \\
+ \beta_1 \left(\frac{F}{r}(1 - e^{-rT}(1 - N(d_0))) - I\right) \quad \text{(C.3)}
\end{aligned}
$$

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

Appendix C.2 The Investment Threshold for the Second Interval: $P \geqslant F$

For $P \geqslant F$, we calculate the value-matching condition in Equation C.4. Similar to the previous section, Equation C.1 represents the optimal investment point where the value of the option (i.e., $D_2 P_F^{*\beta_1}$) is equal to the value of the project (Equation A.22 for the interval $P \geqslant F$) minus the investment cost.

$$\begin{aligned} D_2 P_F^{*\beta_1} &= -A_1 P_F^{*\beta_1}(1 - N(d_{\beta_1})) - \frac{F}{r} e^{-rT}(1 - N(d_0)) \\ &\quad + B_2 P_F^{*\beta_2}(1 - N(d_{\beta_2})) + \frac{P_F^*}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1) + \frac{P_F^*}{r-\mu} e^{-(r-\mu)T} - I \end{aligned} \tag{C.4}$$

We then calculate the smooth-pasting condition in Equation C.5. Again, we calculate the first derivatives of both sides of Equation C.4 with respect to P_F^*, which yields Equation C.5.

$$\begin{aligned} \beta_1 D_2 P_F^{*\beta_1 - 1} &= -\beta_1 A_1 P_F^{*\beta_1 - 1} N(d_{\beta_1}) - A_1 P_F^{*\beta_1} \frac{\partial N(d_{\beta_1})}{\partial P_F^*} + e^{-rT} \frac{F}{r} \frac{\partial N(d_0)}{\partial P_F^*} \\ &\quad + \beta_2 B_2 P_F^{*\beta_2 - 1}(1 - N(d_{\beta_2})) - B_2 P_F^{*\beta_2} \frac{\partial N(-d_{\beta_2})}{\partial P_F^*} \\ &\quad + \frac{1}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) - \frac{P_F^*}{r-\mu} e^{-(r-\mu)T} \frac{\partial N(d_1)}{\partial P_F^*} \\ &\quad + \frac{1}{r-\mu} e^{-(r-\mu)T} \end{aligned} \tag{C.5}$$

As mentioned in the previous section, 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:

$$\begin{aligned} &(\beta_1 - \beta_2) B_2 P_F^{*\beta_2}(1 - N(d_{\beta_2})) + (\beta_1 - 1)\left(\frac{P_F^*}{r-\mu}(1 - e^{-(r-\mu)T} N(d_1)) + \frac{P_F^*}{r-\mu} e^{-(r-\mu)T}\right) \\ &\quad - \beta_1 \left(\frac{F}{r} e^{-rT}(1 - N(d_0)) + I\right) \end{aligned} \tag{C.6}$$

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

Appendix D Proof that the value-matching and smooth-pasting conditions are not met for $P_R^* < F$

This appendix proves that $(C_1(\omega F) - A_1) < 0$. Hence, the value-matching and smooth-pasting conditions are not met for the first branch of the value of the project (i.e.: $P_R^* < F$).

Proof. We know that the value of the option with a price floor of F (i.e., $F(P, F)$) is greater than the value of the option with a price floor of ωF (i.e., $F(P, \omega F)$), because $F \geqslant \omega F$. Hence:

$$F(P, F) \geqslant F(P, \omega F) \tag{D.1}$$

Substituting Equation 15 for $F(P, F)$ and Equation 33 for $F(P, \omega F)$ yields:

$$(V(P^*, F) - I)\left(\frac{P}{P^*}\right)^{\beta_1} \geqslant C_1(\omega F)P^{\beta_1} \tag{D.2}$$

Recall that for $P < F$, $V(P, F) = A_1 P^{\beta 1} + \dfrac{F}{r}$, hence:

$$\left(A_1 P^{*\beta_1} + \frac{F}{r} - I\right)\left(\frac{P}{P^*}\right)^{\beta_1} \geqslant C_1(\omega F)P^{\beta_1} \tag{D.3}$$

Multiplying both sides by $P^{-\beta_1}$ yields:

$$\left(A_1 P^{*\beta_1} + \frac{F}{r} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1} \geqslant C_1(\omega F) \tag{D.4}$$

Simplifying:

$$A_1 + \left(\frac{F}{r} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1} \geqslant C_1(\omega F) \tag{D.5}$$

Hence,

$$C_1(\omega F) - A_1 \leqslant \left(\frac{F}{r} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1} \tag{D.6}$$

Note that, in order to satisfy the value-matching and the smooth-pasting conditions, we know that $\left(\dfrac{F}{r} - I\right) < 0$. Otherwise, investment occurs immediately and generate a risk-free payoff. One of the conditions of real options models is to have a high sunk cost. In other words, to have the value-matching and the smooth-pasting conditions, the value of the project minus investment (NPV) for $P = 0$ should be lower than zero. Hence:

$$C_1(\omega F) - A_1 \leqslant \left(\frac{F}{r} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1} < 0 \tag{D.7}$$

Therefore,

$$C_1(\omega F) - A_1 < 0 \tag{D.8}$$

□

Appendix E Limits of the Value of the Option with a Perpetual Guarantee and Regulatory Uncertainty

This appendix calculates the limits of the value of the option and the investment threshold with a perpetual guarantee and regulatory uncertainty.

Appendix E.1 Limits when $\lambda \to 0$

We prove that the value of the option with regulatory uncertainty, $F_R(P,F)$ (i.e., Equation 45) reduces to the value of the option without regulatory uncertainty $F(P,F)$ (i.e., Equation 15).

The limit of $F_R(P,F)$ when λ goes to 0 is:

$$\lim_{\lambda\to 0} F_R(P,F) = \lim_{\lambda\to 0}\left[\left(V(P_R^*,F) - I - C_1(\omega F)P_R^{*\beta_1}\right)\left(\frac{P}{P_R^*}\right)^{\eta_1} + C_1(\omega F)P^{\beta_1}\right] \quad \text{for } P < F \tag{E.1}$$

Note that $\lim_{\lambda\to 0}\eta_1 = \beta_1$, therefore:

$$\begin{aligned}
\lim_{\lambda\to 0} F_R(P,F) &= \left[\left(V(P_R^*,F) - I - C_1(\omega F)P_R^{*\beta_1}\right)\left(\frac{P}{P_R^*}\right)^{\beta_1} + C_1(\omega F)P^{\beta_1}\right] \\
&= \left(V(P_R^*,F) - I\right)\left(\frac{P}{P_R^*}\right)^{\beta_1} - C_1(\omega F)P_R^{*\beta_1}\left(\frac{P}{P_R^*}\right)^{\beta_1} + C_1(\omega F)P^{\beta_1} \\
&= \left(V(P_R^*,F) - I\right)\left(\frac{P}{P_R^*}\right)^{\beta_1} = F(P,F)
\end{aligned} \tag{E.2}$$

Hence, when λ goes to 0, the value of the option with perpetual guarantee and regulatory uncertainty is equal to Equation 15, i.e the value of the option without a regulatory uncertainty.

Also, when λ goes to 0, it is easy to see that Equation 49 (i.e., the investment threshold with regulatory uncertainty, P_R^*) reduces to Equation 16 (i.e., the investment threshold without regulatory uncertainty, P^*), as shown below:

$$\begin{aligned}
&\lim_{\lambda\to 0}\left[(\eta_1-\beta_2)B_2P_R^{*\beta_2} - (\eta_1-\beta_1)C_1(\omega F)P_R^{*\beta_1} + (\eta_1-1)\frac{P_R^*}{r-\mu} - \eta_1 I\right] \\
&\quad = \left[(\beta_1-\beta_2)B_2P_R^{*\beta_2} - (\beta_1-\beta_1)C_1(\omega F)P_R^{*\beta_1} + (\beta_1-1)\frac{P_R^*}{r-\mu} - \beta_1 I\right] \\
&\quad = \left[(\beta_1-\beta_2)B_2P_R^{*\beta_2} + (\beta_1-1)\frac{P_R^*}{r-\mu} - \beta_1 I\right]
\end{aligned} \tag{E.3}$$

In other words, when the probability of occurring a policy change goes to zero (i.e., the event will not occur), the value of the option $F_R(P,F)$ is the same as $F(P,F)$, which is the value of the option without regulatory uncertainty.

Appendix E.2 Values when $\omega = 1$

Next, we calculate the investment threshold and value of option with regulatory uncertainty when $\omega = 1$, whereby the price floor never changes when jump events occur (i.e., $F = \omega F$). It is straightforward to see that, when $\omega = 1$, the following occurs: (i) $B_2(\omega F)$ in Equation 36 is equal to B_2, (ii) $P^*(\omega F)$ is equal to P^*, (iii) $V(P^*(\omega F), \omega F)$ in Equation 37 is equal to $V(P^*, F)$, and (iv) $C_1(\omega F)$ in Equation 34 is equal to $C_1(F)$. Hence, replacing $\left(B_2 {P^*}^{\beta_2} + \frac{P^*}{r-\mu} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1}$ for $C_1(\omega F)$ in Equation 49 yields:

$$(\eta_1 - \beta_2)B_2 {P^*}^{\beta_2} - (\eta_1 - \beta_1)\left(B_2 {P^*}^{\beta_2} + \frac{P^*}{r-\mu} - I\right)\left(\frac{1}{P^*}\right)^{\beta_1} {P^*}^{\beta_1} + (\eta_1 - 1)\frac{P^*}{r-\mu} - \eta_1 I = 0 \quad \text{(E.4)}$$

Expanding Equation E.4 yields:

$$\eta_1 B_2 {P^*}^{\beta_2} - \beta_2 B_2 {P^*}^{\beta_2} - \eta_1 B_2 {P^*}^{\beta_2} + \beta_1 B_2 {P^*}^{\beta_2} - \eta_1 \frac{P^*}{r-\mu} + \beta_1 \frac{P^*}{r-\mu} + \eta_1 I - \beta_1 I + \eta_1 \frac{P^*}{r-\mu} - \frac{P^*}{r-\mu} - \eta_1 I = 0 \quad \text{(E.5)}$$

Simplifying Equation E.5 yields:

$$-\beta_2 B_2 {P^*}^{\beta_2} + \beta_1 B_2 {P^*}^{\beta_2} + \beta_1 \frac{P^*}{r-\mu} - \beta_1 I - \frac{P^*}{r-\mu} = 0 \quad \text{(E.6)}$$

Re-aranging Equation E.6 yields:

$$(\beta_1 - \beta_2)B_2 {P^*}^{\beta_2} + (\beta_1 - 1)\frac{P^*}{r-\mu} - \beta_1 I = 0 \quad \text{(E.7)}$$

Equation E.7 is equal to Equation 16. Therefore, when $\omega = 1$, the investment threshold of the project with a perpetual guarantee and regulatory uncertainty is equal to the investment threshold of the project with a perpetual guarantee, but without regulatory uncertainty.

In addition, replacing $(V(P^*) - I)\left(\frac{1}{P^*}\right)^{\beta_1}$ for $C_1(\omega F)$ in Equation 45 yields:

$$F_R(P, F) = \begin{cases} \left(V(P^*, F) - I - (V(P^*, F) - I)\left(\frac{P^*}{P^*}\right)^{\beta_1}\right)\left(\frac{P}{P^*_R}\right)^{\eta_1} \\ + (V(P^*, F) - I)\left(\frac{P}{P^*}\right)^{\beta_1} & \text{for } P < P^* \\ V(P, F) - I & \text{for } P \geqslant P^* \end{cases} \quad \text{(E.8)}$$

Hence,

$$F_R(P, F) = \begin{cases} (V(P^*, F) - I)\left(\frac{P}{P^*}\right)^{\beta_1} & \text{for } P < P^* \\ V(P, F) - I & \text{for } P \geqslant P^* \end{cases} \quad \text{(E.9)}$$

Note that Equation E.9 is equal to Equation 15. Hence, when $\omega = 1$, the value of the option with a perpetual guarantee and regulatory uncertainty, $F_R(P, F)$ is equal to the value of the project with a perpetual guarantee and without regulatory uncertainty, $F(P, F)$.

Appendix E.3 Limits when $\lambda \to +\infty$

Finally, we check the investment threshold and value of option with regulatory uncertainty when $\lambda \to +\infty$. In this condition, the event certainly occurs. Hence, the investment threshold and the value of the option with regulatory uncertainty reduce to the equations without regulatory uncertainty where the price floor is ωF instead of F.

The value of the option of a project with regulatory uncertainty is:

$$F_R(P,F) = \begin{cases} (V(P_R^*, F) - I - C_1(\omega F) P_R^{*\beta_1}) \left(\dfrac{P}{P_R^*}\right)^{\eta_1} + C_1(\omega F) P^{\beta_1} & \text{for } P < P_R^* \\ \\ V(P,F) - I & \text{for } P \geqslant P_R^* \end{cases} \tag{E.10}$$

In the first branch (i.e., $P < P_R^*$), it is easy to show that the term $\left(\dfrac{P}{P_R^*}\right)^{\eta_1}$ goes to 0, when $\lambda \to +\infty$ because from Equation 40, $\lim_{\lambda \to +\infty} \eta_1 = +\infty$. Hence, Equation E.10 reduces to the following:

$$F_R(P,F) = \begin{cases} C_1(\omega F) P^{\beta_1} & \text{for } P < P_R^* \\ \\ V(P,F) - I & \text{for } P \geqslant P_R^* \end{cases} \tag{E.11}$$

Substituting $(V(P^*(\omega F), \omega F) - I)\left(\dfrac{1}{P^*(\omega F)}\right)^{\beta_1}$ for $C_1(\omega F)$ in Equation E.11 yields:

$$F_R(P,F) = \begin{cases} (V(P^*(\omega F), \omega F) - I)\left(\dfrac{P}{P^*(\omega F)}\right)^{\beta_1} & \text{for } P < P^*(\omega F) \\ \\ V(P, \omega F) - I & \text{for } P \geqslant P^*(\omega F) \end{cases} \tag{E.12}$$

Hence, when λ goes to $+\infty$, the value of the option with a perpetual guarantee and regulatory uncertainty, $F_R(P,F)$ is equal to the value of the project without regulatory uncertainty where the price floor is equal to ωF instead of F (i.e., $F(P, \omega F)$).

Appendix F Limits of the Finite Guarantee with Regulatory Uncertainty

This appendix calculates the limits of the value of the option and the investment threshold with a finite guarantee and regulatory uncertainty.

Appendix F.1 Limits when $\lambda \to 0$

We prove that the value of the option with regulatory uncertainty $F_{FR}(P, F)$ (i.e., Equation 55) reduces to the value of the option without regulatory uncertainty $F_F(P, F)$ (i.e., Equation 25).

The limit of $F_R(P, F)$ when $\lambda \to 0$ is:

$$\lim_{\lambda \to 0} F_{FR}(P, F) = \lim_{\lambda \to 0} \left[(V_F(P^*_{FR}, F) - I - D_1(\omega F) P^{*\beta_1}_{FR}) \left(\frac{P}{P^*_{FR}} \right)^{\eta_1} + D_1(\omega F) P^{\beta_1} \right] \text{ for } P < P^*_{FR} \quad \text{(F.1)}$$

Recall that $\lim_{\lambda \to 0} \eta_1 = \beta_1$, therefore:

$$\begin{aligned} \lim_{\lambda \to 0} F_{FR}(P, F) &= (V_F(P^*_{FR}, F) - I - D_1(\omega F) P^{*\beta_1}_{FR}) \left(\frac{P}{P^*_{FR}} \right)^{\beta_1} + D_1(\omega F) P^{\beta_1} \\ &= (V_F(P^*_{FR}, F) - I) \left(\frac{P}{P^*_{FR}} \right)^{\beta_1} - D_1(\omega F) P^{\beta_1} + D_1(\omega F) P^{\beta_1} \\ &= (V_F(P^*_{FR}, F) - I) \left(\frac{P}{P^*_{FR}} \right)^{\beta_1} \text{ for } P < P^*_{FR} \end{aligned} \quad \text{(F.2)}$$

Hence, when λ goes to 0, the value of the option with finite guarantee and regulatory uncertainty is equal to Equation 25, i.e the value of the option without regulatory uncertainty.

Also, when λ goes to 0, it is straightforward to see that Equation 56 (i.e., the investment threshold with regulatory uncertainty, P^*_{FR}) reduces to Equation 26 (i.e., the investment threshold without regulatory uncertainty, P^*_F), as shown below.

The equations to calculate the investment threshold with regulatory uncertainty are:

$$\begin{cases} (\eta_1 - \beta_1)(A_1 N(d_{\beta_1}) - D_1(\omega F)) P^{*\beta_1}_{FR} - (\eta_1 - \beta_2) B_2 P^{*\beta_2}_{FR} N(d_{\beta_2}) \\ +\eta_1 \left(\frac{F}{r} - \frac{F}{r} e^{-rT} (1 - N(d_0)) - I \right) \\ +(\eta_1 - 1) \frac{P^*_{FR}}{r - \mu} e^{-(r-\mu)T} (1 - N(d_1)) = 0 & \text{for } P^*_{FR} < F \\ \\ -(\eta_1 - \beta_1)(A_1 (1 - N(d_{\beta_1})) + D_1(\omega F)) P^{*\beta_1}_{FR} \\ +(\eta_1 - \beta_2) B_2 P^{*\beta_2}_{FR} (1 - N(d_{\beta_2})) \\ +(\eta_1 - 1) \frac{P^*_{FR}}{r - \mu} (1 - e^{-(r-\mu)T} N(d_1) \\ +e^{-(r-\mu)T}) - \eta_1 \left(\frac{F}{r} e^{-rT} (1 - N(d_0)) + I \right) = 0 & \text{for } P^*_{FR} \geqslant F \end{cases} \quad \text{(F.3)}$$

We know that $\lim_{\lambda \to 0} \eta_1 = \beta_1$. Thus, the first branch of Equation F.3 yields the following equation when $\lambda \to 0$:

$$- (\beta_1 - \beta_2) B_2 P_{FR}^{*\beta_2} N(d_{\beta_2}) + \beta_1 \left(\frac{F}{r} - \frac{F}{r} e^{-rT}(1 - N(d_0)) - I \right) + (\beta_1 - 1) \frac{P_{FR}^*}{r - \mu} e^{-(r-\mu)T}(1 - N(d_1)) = 0 \quad \text{(F.4)}$$

In addition, for $P_{FR}^* \geqslant F$, the second branch of Equation F.3 yields the following equation when $\lambda \to 0$:

$$(\beta_1 - \beta_2) B_2 P_{FR}^{*\beta_2}(1 - N(d_{\beta_2})) + (\beta_1 - 1) \frac{P_{FR}^*}{r - \mu}(1 - e^{-(r-\mu)T} N(d_1) + e^{-(r-\mu)T}) - \beta_1 \left(\frac{F}{r} e^{-rT}(1 - N(d_0)) + I \right) = 0 \text{ for } P \geqslant P_{FR}^* \quad \text{(F.5)}$$

Hence, the two equations above reduce to the equations of the investment threshold without regulatory uncertainty.

Appendix F.2 Values when $\omega = 1$

Next, we calculate the investment threshold and value of option with regulatory uncertainty when $\omega = 1$, whereby the price floor never changes when jump events occur (i.e., $F = \omega F$). It is straightforward to see that when $\omega = 1$, the following occurs: (i) $B_2(\omega F)$ in Equation 36 is equal to B_2, (ii) $A_1(\omega F)$, which is equal to Equation 9 where we substitute ωF for F is equal to A_1,(ii) $P_F^*(\omega F)$ is equal to P_F^*, (iii) $V_F(P^*(\omega F), \omega F)$, which we find by substituting ωF for F in Equation 21 is equal to $V_F(P^*, F)$, and (iv) $D_1(\omega F)$ in Equation 52 is equal to $D_1(F)$. Hence, substituting $(V_F(P^*(F), F) - I) \left(\frac{1}{P^*(F)} \right)^{\beta_1}$ for $D_1(\omega F)$ in Equation 56 yields:

$$\begin{cases} (\eta_1 - \beta_1) \left(A_1 N(d_{\beta_1}) - (V_F(P^*(F), F) - I) \left(\frac{1}{P^*(F)} \right)^{\beta_1} \right) P_{FR}^{*\beta_1} \\ -(\eta_1 - \beta_2) B_2 P_{FR}^{*\beta_2} N(d_{\beta_2}) \\ +\eta_1 \left(\frac{F}{r} - \frac{F}{r} e^{-rT}(1 - N(d_0)) - I \right) \\ +(\eta_1 - 1) \frac{P_{FR}^*}{r - \mu} e^{-(r-\mu)T}(1 - N(d_1)) = 0 & \text{for } P_{FR}^* < F \\ \\ -(\eta_1 - \beta_1) \left(A_1 (1 - N(d_{\beta_1})) + (V_F(P^*(F), F) - I) \left(\frac{1}{P^*(F)} \right)^{\beta_1} \right) P_{FR}^{*\beta_1} \\ +(\eta_1 - \beta_2) B_2 P_{FR}^{*\beta_2}(1 - N(d_{\beta_2})) \\ +(\eta_1 - 1) \frac{P_{FR}^*}{r - \mu}(1 - e^{-(r-\mu)T} N(d_1) \\ +e^{-(r-\mu)T}) - \eta_1 \left(\frac{F}{r} e^{-rT}(1 - N(d_0)) + I \right) = 0 & \text{for } P_{FR}^* \geqslant F \end{cases} \quad \text{(F.6)}$$

When $P_{FR}^* < F$, we substitute Equation 21 for $(V_F(P^*(F), F)$ in Equation F.6, which yields:

$$
\begin{aligned}
&(\eta_1-\beta_1)\left(A_1N(d_{\beta_1})\right)P_F^{*\beta_1}-(\eta_1-\beta_1)A_1P_F^{*\beta_1}N(d_{\beta_1})\\
&\quad-(\eta_1-\beta_1)\left(\frac{F}{r}(1-e^{-rT}(1-N(d_0)))-B_2P_F^{*\beta_2}N(d_{\beta_2})-\frac{P_F^*}{r-\mu}e^{-(r-\mu)T}(N(d_1)-1)\right)\\
&\qquad+(\eta_1-\beta_1)I-(\eta_1-\beta_2)B_2P_F^{*\beta_2}N(d_{\beta_2})\\
&\qquad+\eta_1\left(\frac{F}{r}-\frac{F}{r}e^{-rT}(1-N(d_0))-I\right)\\
&\qquad+(\eta_1-1)\frac{P_F^*}{r-\mu}e^{-(r-\mu)T}(1-N(d_1))=0 \quad \text{(F.7)}
\end{aligned}
$$

Simplifying Equation F.7 yields:

$$
\begin{aligned}
&-(\beta_1-\beta_2)B_2P_F^{*\beta_2}N(d_{\beta_2})-(\beta_1-1)\frac{P_F^*}{r-\mu}e^{-(r-\mu)T}(N(d_1)-1)\\
&\qquad+\beta_1\left(\frac{F}{r}(1-e^{-rT}(1-N(d_0)))-I\right)=0 \quad \text{(F.8)}
\end{aligned}
$$

And for $P_{FR}^*\geqslant F$, substituting Equation 21 to $(V_F(P^*(F),F)$ yields:

$$
\begin{aligned}
&-(\eta_1-\beta_1)A_1(1-N(d_{\beta_1}))P_F^{*\beta_1}+(\eta_1-\beta_1)A_1P_F^{*\beta_1}(1-N(d_{\beta_1}))\\
&-(\eta_1-\beta_1)(-\frac{F}{r}e^{-rT}(1-N(d_0))+B_2P_F^{*\beta_2}(1-N(d_{\beta_2}))+\frac{P_F^*}{r-\mu}(1-e^{-(r-\mu)T}N(d_1)+e^{-(r-\mu)T})-I)\\
&\qquad+(\eta_1-\beta_2)B_2P_F^{*\beta_2}(1-N(d_{\beta_2}))\\
&\qquad+(\eta_1-1)\frac{P_F^*}{r-\mu}(1-e^{-(r-\mu)T}N(d_1)\\
&\qquad+e^{-(r-\mu)T})-\eta_1\left(\frac{F}{r}e^{-rT}(1-N(d_0))+I\right)=0 \quad \text{(F.9)}
\end{aligned}
$$

Simplifying Equation F.9, yields:

$$
\begin{aligned}
&(\beta_1-\beta_2)B_2P_F^{*\beta_2}(1-N(d_{\beta_2}))+(\beta_1-1)\left(\frac{P_F^*}{r-\mu}(1-e^{-(r-\mu)T}N(d_1))+e^{-(r-\mu)T}\right)\\
&\qquad-\beta_1\left(\frac{F}{r}e^{-rT}(1-N(d_0))+I\right)=0 \quad \text{(F.10)}
\end{aligned}
$$

Hence, when $\omega=1$, the investment threshold of the project with regulatory uncertainty is equal to the investment threshold of the project without regulatory uncertainty (i.e., Equation 26).

For the value of the option, we replace $(V(P_F^*,F)-I)\left(\frac{1}{P_F^*}\right)^{\beta_1}$ for $D_1(\omega F)$ in Equation 55 and P_F^* for P_{FR}^*. Thus, yielding:

$$
F_{FR}(P,F)=\begin{cases}(V_F(P_F^*,F)-I-(V(P_F^*,F)-I)\left(\frac{1}{P_F^*}\right)^{\beta_1}P_F^{*\beta_1})\left(\frac{P}{P_F^*}\right)^{\eta_1} & \\ +(V(P_F^*,F)-I)\left(\frac{1}{P_F^*}\right)^{\beta_1}P^{\beta_1} & \text{for } P<P_F^* \\ V_F(P,F)-I & \text{for } P\geqslant P_F^*\end{cases} \quad \text{(F.11)}
$$

Simplifying Equation F.11 yields:

$$F_{FR}(P,F) = \begin{cases} (V(P_F^*,F) - I)\left(\dfrac{P}{P_F^*}\right)^{\beta_1} & \text{for } P < P_F^* \\ \\ V(P,F) - I & \text{for } P \geqslant P_F^* \end{cases} \tag{F.12}$$

Note that Equation F.12 is equal to Equation 25. Therefore, when $\omega = 1$, the value of the option with regulatory uncertainty, $F_{FR}(P,F)$ is equal to the value of the option without regulatory uncertainty, $F_F(P,F)$.

Appendix F.3 Limits when $\lambda \to +\infty$

Next, we check the investment threshold and value of option of the project with regulatory uncertainty when $\lambda \to +\infty$. The limit when $\lambda \to +\infty$ means that the event occurs immediately. Hence, the investment threshold and the value of the option with regulatory uncertainty reduce to the values without regulatory uncertainty, where the price floor is ωF instead of F.

The value of the option of the project with regulatory uncertainty is:

$$F_{FR}(P,F) = \begin{cases} (V_F(P_{FR}^*,F) - I - D_1(\omega F)P_{FR}^{*\beta_1})\left(\dfrac{P}{P_{FR}^*}\right)^{\eta_1} + D_1(\omega F)P^{\beta_1} & \text{for } P < P_{FR}^* \\ \\ V_F(P,F) - I & \text{for } P \geqslant P_{FR}^* \end{cases} \tag{F.13}$$

It is easy to see that in the first branch, i.e: $P < P_{FR}^*$, the term $\left(\dfrac{P}{P_{FR}^*}\right)^{\eta_1}$ goes to 0, when $\lambda \to +\infty$ because from Equation 40, $\lim_{\lambda \to +\infty} \eta_1 = +\infty$. Hence, Equation F.13 reduces to the following:

$$F_{FR}(P,F) = \begin{cases} D_1(\omega F)P^{\beta_1} & \text{for } P < P_{FR}^* \\ \\ V(P,F) - I & \text{for } P \geqslant P_{FR}^* \end{cases} \tag{F.14}$$

Substituting $D_1(\omega F)$ by $(V_F(P_F^*(\omega F),\omega F) - I)\left(\dfrac{1}{P_F^*(\omega F)}\right)^{\beta_1}$ (Equation 52) yields:

$$F_{FR}(P,F) = \begin{cases} (V_F(P_F^*(\omega F),\omega F) - I)\left(\dfrac{P}{P_F^*(\omega F)}\right)^{\beta_1} & \text{for } P < P_F^*(\omega F) \\ \\ V(P,\omega F) - I & \text{for } P \geqslant P_F^*(\omega F) \end{cases} \tag{F.15}$$

Hence, when λ goes to $+\infty$, the value of the option of a project with regulatory uncertainty, $F_{FR}(P,F)$ is equal to the value of the option of a project without regulatory and with a price floor of ωF instead of F, $F_F(P,\omega F)$.

Appendix F.4 Limits when $T \to +\infty$

Finally, we prove that the value of the option of a project with a finite guarantee and regulatory uncertainty when $T \to +\infty$ is equal to the value of the option of a project with a perpetual guarantee and regulatory uncertainty. We first demonstrate that the investment threshold of both are the same. For $P \geqslant P_{FR}^*$, the investment threshold of a project with finite guarantee and regulatory uncertainty (i.e., Equation 56) is:

$$- (\eta_1 - \beta_1)(A_1(1 - N(d_{\beta_1})) + D_1(\omega F))P_{FR}^{*\beta_1} + (\eta_1 - \beta_2)B_2 P_{FR}^{*\beta_2}(1 - N(d_{\beta_2})) + (\eta_1 - 1)\frac{P_{FR}^*}{r-\mu}(1 - e^{-(r-\mu)T}N(d_1) + e^{-(r-\mu)T}) - \eta_1\left(\frac{F}{r}e^{-rT}(1 - N(d_0)) + I\right) = 0 \quad \text{(F.16)}$$

When $T \to +\infty$, we have:

$$- (\eta_1 - \beta_1)(A_1(1 - N(d_{\beta_1})) + D_1(\omega F))P_{FR}^{*\beta_1} + (\eta_1 - \beta_2)B_2 P_{FR}^{*\beta_2}(1 - N(d_{\beta_2})) + (\eta_1 - 1)\frac{P_{FR}^*}{r-\mu} - \eta_1 I = 0 \quad \text{(F.17)}$$

In addition, as we demonstrated in Appendix B: (i) $\lim_{T\to\infty} N(d_{\beta_2}) = 0$ and, (ii) $\lim_{T\to\infty} N(d_{\beta_1}) = 1$. Hence, Equation F.17 yields:

$$- (\eta_1 - \beta_1)(D_1(\omega F))P_{FR}^{*\beta_1} + (\eta_1 - \beta_2)B_2 P_{FR}^{*\beta_2} + (\eta_1 - 1)\frac{P_{FR}^*}{r-\mu} - \eta_1 I = 0 \quad \text{(F.18)}$$

Also, it is easy to see that $\lim_{T\to+\infty} D_1(\omega F) = C_1(\omega F)$, since we demonstrated in Appendix B that the value of the project with a finite guarantee is the same as the value of the project of a perpetual guarantee when $T \to +\infty$. Therefore, when $T \to +\infty$, the investment threshold of a project with a finite guarantee and regulatory uncertainty is the same as the investment threshold of a project with a perpetual guarantee and regulatory uncertainty.

The value of the option of a project with finite guarantee and regulatory uncertainty (i.e., Equation 55) is:

$$F_{FR}(P,F) = \begin{cases} (V_F(P_{FR}^*, F) - I - D_1(\omega F)P_{FR}^{*\beta_1})\left(\frac{P}{P_{FR}^*}\right)^{\eta_1} + D_1(\omega F)P^{\beta_1} & \text{for } P < P_{FR}^* \\ V_F(P,F) - I & \text{for } P \geqslant P_{FR}^* \end{cases} \quad \text{(F.19)}$$

Since $\lim_{T\to+\infty} D_1(\omega F) = C_1(\omega F)$ and $\lim_{T\to+\infty} P_{FR}^* = P_R^*$, Equation F.19 yields:

$$F_{FR}(P,F) = \begin{cases} (V(P_R^*, F) - I - C_1(\omega F)P_R^{*\beta_1})\left(\frac{P}{P_R^*}\right)^{\eta_1} + C_1(\omega F)P^{\beta_1} & \text{for } P < P_R^* \\ V_F(P,F) - I & \text{for } P \geqslant P_R^* \end{cases} \quad \text{(F.20)}$$

which is the same as Equation 45 (i.e., the value of the option with perpetual guarantee and regulatory uncertainty).

Appendix G Derivative of the Optimal Threshold with Respect to T

This appendix calculates the derivative of the optimal threshold with respect to T and evaluates the sign. Therefore, we derive Equation 26 with respect to T. Note that the partial derivative of β_1, β_2, and B_2 with respect to T is zero because these terms do not depend on T. In addition, recall that the partial derivatives of the cumulative distribution function cancel across the betas (Shackleton & Wojakowski 2007).

We first calculate the derivative of P_F^* with respect to T for the first branch (i.e.: $P_F^* < F$)

$$-(\beta_1-\beta_2)B_2\beta_2 {P_F^*}^{\beta_2-1}\frac{\partial P_F^*}{\partial T}N(d_{\beta_2})+(\beta_1-1)\frac{e^{-(r-\mu)T}}{r-\mu}(1-N(d_1))\frac{\partial P_F^*}{\partial T} - (\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1))+\beta_1 F e^{-rT}(1-N(d_0))=0 \quad (G.1)$$

Re-aranging Equation G.1 yields:

$$\left(-(\beta_1-\beta_2)B_2\beta_2 {P_F^*}^{\beta_2-1}N(d_{\beta_2})+(\beta_1-1)\frac{e^{-(r-\mu)T}}{r-\mu}(1-N(d_1))\right)\frac{\partial P_F^*}{\partial T} = (\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1))-\beta_1 F e^{-rT}(1-N(d_0)) \quad (G.2)$$

As $\beta_1 > 1$, $\beta_2 < 0$, $N(d_\beta) < 1$ and $B_2 > 0$, it is straightforward to see that the term in the left side of $\frac{\partial P_F^*}{\partial T}$ in Equation G.2 is always positive. In addition, we know that $P_F^* < F$ because we calculated the derivative for the first branch, thus $\beta_1 F e^{-rT}(1-N(d_0)) > (\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1))$. Hence, $\frac{\partial P_F^*}{\partial T}$ is negative.

For the second branch (i.e.: $P_F^* \geqslant F$), the derivative of the trigger with respect to T is:

$$(\beta_1-\beta_2)B_2\beta_2 {P_F^*}^{\beta_2-1}\frac{\partial P_F^*}{\partial T}(1-N(d_{\beta_2}))+\frac{(\beta_1-1)}{r-\mu}\frac{\partial P_F^*}{\partial T}\left(1-e^{-(r-\mu)T}N(d_1)+e^{-(r-\mu)T}\right) - (\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1))+\beta_1 F e^{-rT}(1-N(d_0))=0 \quad (G.3)$$

Re-aranging Equation G.4 yields:

$$\left((\beta_1-\beta_2)B_2\beta_2 {P_F^*}^{\beta_2-1}(1-N(d_{\beta_2}))+\frac{(\beta_1-1)}{r-\mu}\left(1-e^{-(r-\mu)T}N(d_1)+e^{-(r-\mu)T}\right)\right)\frac{\partial P_F^*}{\partial T} = (\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1))-\beta_1 F e^{-rT}(1-N(d_0)) \quad (G.4)$$

As this is the trigger of the second branch and $P_F^* \geqslant F$ then $(\beta_1-1)P_F^* e^{-(r-\mu)T}(1-N(d_1)) > \beta_1 F e^{-rT}(1-N(d_0))$; consequently, the right hand side of the Equation G.4 is positive. In addition, the left hand side of Equation G.4 is negative because $\beta_2 < 0$. Hence, $\frac{\partial P_F^*}{\partial T}$ is negative.

References

Abadie, Luis M., José M. Chamorro & Mikel González-Eguino (2013), 'Valuing uncertain cash flows from investments that enhance energy efficiency', *Journal of Environmental Management* **116**, 113 – 124.

Abolhosseini, Shahrouz & Almas Heshmati (2014), 'The main support mechanisms to finance renewable energy development', *Renewable and Sustainable Energy Reviews* **40**, 876 – 885.

Adkins, Roger & Dean Paxson (2016), 'Subsidies for renewable energy facilities under uncertainty', *The Manchester School* **84**(2), 222 – 250.

Adkins, Roger & Dean Paxson (2017), Risk sharing with collar options in infrastructure investments, *in* 'Real Options Conference'.

Boomsma, Trine Krogh & Kristin Linnerud (2015), 'Market and policy risk under different renewable electricity support schemes', *Energy* **89**, 435 – 448.

Boomsma, Trine Krogh, Nigel Meade & Stein-Erik Fleten (2012), 'Renewable energy investments under different support schemes: A real options approach', *European Journal of Operational Research* **220**(1), 225 – 237.

Brennan, Michael J & Eduardo S Schwartz (1985), 'Evaluating natural resources investments', *The Journal of Business* **58**, 135–57.

Butler, Lucy & Karsten Neuhoff (2008), 'Comparison of feed-in tariff, quota and auction mechanisms to support wind power development', *Renewable Energy* **33**(8), 1854 – 1867.

Ceseña, E.A. Martínez, J. Mutale & F. Rivas-Dávalos (2013), 'Real options theory applied to electricity generation projects: A review', *Renewable and Sustainable Energy Reviews* **19**, 573 – 581.

Clancy, D., J.P. Breen, F. Thorne & M. Wallace (2012), 'The influence of a renewable energy feed in tariff on the decision to produce biomass crops in ireland', *Energy Policy* **41**, 412 – 421.

Couture, Toby D., Karlynn Cory Claire Kreycik & Emily Williams (2010), A policymaker's guide to feed-in tari policy design, Technical Report NREL/TP-6A2-44849, NREL.

Couture, Toby & Yves Gagnon (2010), 'An analysis of feed-in tariff remuneration models: Implications for renewable energy investment', *Energy Policy* **38**(2), 955–965.

DCCAE (2016), 'Irish REFIT scheme'.
URL: *http://www.dccae.gov.ie/energy/en-ie/Renewable-Energy/Pages/Refit-Schemes-Landing-Page.aspx*

Deane, J.P., G. Dalton & B.P. Ó Gallachóir (2012), 'Modelling the economic impacts of 500 {MW} of wave power in ireland', *Energy Policy* **45**, 614 – 627.

Dixit, A.K & R.S Pindyck (1994), *Investment Under Uncertainty*, Princeton University Press, Princeton, New Jersey.

Doherty, Ronan & Mark O'Malley (2011), 'The efficiency of ireland's renewable energy feed-in tariff (refit) for wind generation', *Energy Policy* **39**, 4911 – 4919.

EIA (2017), Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook 2017, Technical report, U.S. Energy Information Administration.

Enevoldsen, Peter & Scott Victor Valentine (2016), 'Do onshore and offshore wind farm development patterns differ?', *Energy for Sustainable Development* **35**, 41 – 51.

EWEA (2009), 'The Economics of Wind Energy'.
URL: *https://www.wind-energy-the-facts.org/index-43.html*

Grubb, Michael (2004), 'Technology innovation and climate change policy: an overview of issues and options', *Keio Economic Studies* **41**(2), 103–132.

Kim, Kyoung-Kuk & Chi-Guhn Lee (2012), 'Evaluation and optimization of feed-in tariffs', *Energy Policy* **49**, 192–203.

Klessmann, Corinna, Patrick Lamers, Mario Ragwitz & Gustav Resch (2010), 'Design options for cooperation mechanisms under the new european renewable energy directive', *Energy Policy* **38**(8), 4679–4691.

Lesser, Jonathan A. & Xuejuan Su (2008), 'Design of an economically efficient feed-in tariff structure for renewable energy development', *Energy Policy* **36**(3), 981 – 990.

Lo, Andrew W. & Jiang Wang (1995), 'Implementing option pricing models when asset returns are predictable', *Journal of Finance* **50**, 87 – 129.

McDonald, Robert & Daniel Siegel (1986), 'The value of waiting to invest', *The Quarterly Journal of Economics* **101**(707-728).

Megaw, Nicholas (2015), 'Energy groups axe UK renewable projects (Financial Times)'.
URL: *https://www.ft.com/content/517aabd6-7343-11e5-bdb1-e6e4767162cc*

Myers, S.C (1977), 'Determinants of corporate borrowing', *Journal of Financial Economics* **5**, 147–175.

Pindyck, Robert S (1988), 'Irreversible investment, capacity choice, and the value of', *The American Economic Review* **78**(5), 969.

Pindyck, R.S. (2001), 'The dynamics of commodity spot and futures markets: A primer', *Energy Journal* **22**(1 - 29).

Ritzenhofen, Ingmar & Stefan Spinler (2016), 'Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty — a real options analysis', *Energy Economics* (53), 76–89.

Schallenberg-Rodriguez, Julieta & Reinhard Haas (2012), 'Fixed feed-in tariff versus premium: A review of the current spanish system', *Renewable and Sustainable Energy Reviews* **16**(1), 293 – 305.

Shackleton, Mark & Rafal Wojakowski (2007), 'Finite maturity caps and floors on continuous flows', *Journal of Economic Dynamics & Control* **31**, 3843–3859.

Tourinho, Octavio Augusto Fontes (1979), The valuation of reserves of natural resources: an option pricing approach, PhD thesis, University of California, Berkeley.

Wiser, R., C. Namovicz, M. Gielecki & R. Smith (2007), 'Renewables portfolio standards: A factual introduction to experience from the united states', *Ernest Orland Lawrence Berkeley National Laboratory, LBNL-62569* .

Woods, Lucy (2014), 'Switzerland cuts solar tariffs by up to 23% (PV Tech)'.
URL: *https://www.pv-tech.org/news/switzerland_cuts_solar_tariff*