Investing in electricity production under a reliability options scheme

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Abstract

Reliability Options (ROs) are used to enhance the security of supply in electricity systems. When a power producer writes a RO, s/he agrees to set a cap on the price of electricity that s/he cashes. In return, the system operator, i.e. the party that is buying the option, pays to the option issuer a fixed premium. In this paper we analyze how ROs affect the timing and value of investments in the energy sector and we show under what conditions they can be used as investment stimuli. We prove that, contrarily to what is expected, ROs can **potentially** harm the security of supply by delaying the adoption of new capacity and by reducing the value of investing in it. To avoid such a result, a careful setting of the relevant parameters is needed.

KEYWORDS: reliability options; electricity markets; investment analysis; real options

JEL CLASSIFICATION: Q40, D80

1 Introduction

As is well known in the theoretical literature of electricity economics, the equilibrium of perfectly competitive electricity markets delivers the efficient level of power capacity, that is, the level at which the marginal investment cost equals the marginal loss attributed to the energy demand that remains unserved.[1] This implies that it would be unnecessary to provide an explicit remuneration for power capacity since the electricity market already provides enough incentives for new investments.

However, when moving from the first-best analysis to the real-world evaluation, several scholars (see e.g. Cramton and Stoft, 2006; Joskow and Tirole, 2007; Joskow, 2007, 2008; Joskow and Wolfram, 2012; Cramton and Ockenfels, 2012; Cramton et al., 2013) have argued that there exist electricity-specific market failures that can impede reaching the first-best outcome. The limited and costly storability of electricity coupled with the need to maintain the system balanced in real time, imply that whenever there is not enough capacity to serve the load, the latter has to be shed. This means that customers might experience power outages even if they highly need power and express the willingness to pay for it. This is the so-called *security of supply* problem.

Explicit remuneration of capacity through Capacity Remuneration Mechanisms (CRMs) can solve this problem.[2] There exist several electricity markets in which CRMs of different forms are

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[1]See for instance, ch. 21 in Creti and Fontini (2019).

[2]See Rodilla and Batlle (2013) and Creti and Fontini (2019).

in use.[3] For instance, *capacity payments* are explicit, administratively set, payments to power producers. *Capacity auctions* are procurement auctions through which the System Operator (SO) remunerates a given amount of generation capacity.[4] *Capacity obligation* is the obligation for load serving entities to hold enough capacity to serve the load. *Strategic reserves* have to do with the withdrawal from the market, and attribution to the SO, of some physical capacity when needed. On the contrary, markets that have no CRMs are called *energy-only* markets.

A CRM that is gaining momentum is a specific form of capacity auction in which power producers sell Reliability Options (ROs) to the SO. Originally proposed by Vázquez et al. (2002), Bidwell (2005), Oren (2005) and firstly implemented in Colombia (Cramton and Stoft, 2007), ROs are also adopted in ISO-New England (FERC, 2014), Ireland (SEM, 2015, 2016a, and 2016b) and in Italy (Mastropietro et al., 2018; TERNA, 2019).

In a nutshell, ROs have the form of swaps on power production. They are sold by power producers to the SO in exchange for a premium. In return, the sellers of the ROs agree to supply energy to the market and return to the SO the extra revenues that they obtain from prices rising above a predetermined level called the strike price of the RO. The return of these extra revenues, also called *implicit penalty*, discourages any opportunistic behavior on the producers' side who might otherwise be tempted to withdraw capacity from the market in an attempt to benefit from price spikes.

Vázquez, et al. (2002), Bidwell (2005) and Oren (2005) introduce ROs and show how they function. Cramton et al. (2013), Battle et al. (2015) and Bhagwat and Meeus (2019) further discuss their features. However, all these papers present qualitative discussions on ROs. To the best of our knowledge, the only paper that quantitatively analyzes the properties of ROs is Andreis et al. (2020). In that work, the authors provide semi-explicit formulas to calculate the financial value of a RO. In order to do so, they consider a hypothetical existing power plant, assume that the overall amount of capacity is fixed and calculate the value of the RO as a financial option. They show how to calculate the arbitrage-free value of a RO that would emerge in a well diversified financial market.

Here, we tackle a different issue. For the power plant that is writing a RO, the RO is a tool to replace stochastic future cash flows, i.e. profits generated by selling electricity at a future time point, with deterministic present ones, i.e. the RO premium. While it is true that in any arbitrage-free financial market where ROs are correctly valued the power producer should be indifferent between participating in an *energy-only* market and an energy market employing ROs, in a real-world setting, market failures can make the issuing of ROs an attractive alternative. In this case, the literature (Joskow and Tirole, 2007, Cramton and Ockenfels, 2012, Cramton et al., 2013) claims that ROs should allow power producers to hedge their investment risk stimulating, as a result, the installment of new capacity.

In this paper, we assess whether ROs are effective in fostering investments in power supply, given that their price can differ from the arbitrage-free equilibrium value, and analyze to what extent their effectiveness depends on their parameters and on the power price. We do so by explicitly studying the impact of a RO scheme on the behavior of a potential investor who is contemplating entering the electricity market. In particular, **we pose and answer two research questions:**

[3] In the USA, the Pennsylvania New Jersey Maryland ISO (PJM), Midcontinent ISO (MISO), ISO New England (ISO-NE), New York ISO (NYISO) and California ISO (CAISO) employ CRMs. In Europe CRMs are used in several national markets, including Germany, France, UK, Italy, Ireland, Spain and Greece. In South America the national markets of Brazil, Colombia, Chile and Peru also use CRMs. For more details, see ch. 23 in Creti and Fontini (2019).

[4] In this paper we denote generically as the SO the entity that balances the grid in the short-run and has the responsibility of ensuring *security of supply* (alone or shared with some other entities). In the USA, this entity is the Independent System Operator (ISO) whereas in Europe it is the Transmission System Operator (TSO).

"How does the use of a RO scheme affect the timing of investment in new capacity?" and "What is the effect of the implementation of this scheme on the value of the option to make such an investment?".

We do so by developing a real options model. This allows to properly account for sunk investment costs (e.g. the cost of setting up the power plant), uncertain future payoffs (e.g. volatile prices of electricity) and temporal flexibility (e.g. the option to postpone the investment). The real options approach builds on the idea that the option to undertake an investment project is analogous to an American call option on a real asset. Hence, when evaluating an investment option characterized by uncertainty and irreversibility, the potential investor needs to factor in that at the time of the investment s/he forgoes the option to reconsider the investment decision at some future time point when the uncertainty will be, naturally, partly resolved.

Within this framework, we find the following. First, we compute the optimal investment threshold and the value of the option to invest in a power plant when the RO scheme is in place. We show that the effect of the implementation of the RO scheme on the behavior of a potential investor depends on whether the electricity market is long or short in capacity at the time of the investment.

If the electricity market is long at the time of the investment, i.e. if the strike price of the RO is larger than the optimal investment threshold chosen by the potential investor, the application of a RO scheme is favoring the acceleration of the investment in new capacity. This happens because, on one hand, the timing decision of the potential investor is unaffected by the upper bound that the RO scheme is setting on electricity prices whereas, on the other, the investor is benefiting from the premium that the scheme is paying. Consequently, the potential investor opts for investing earlier.

As for the effect of the RO scheme on the value of the option to invest in new capacity, this is shown to be ambiguous. For a given strike price, we identify the minimum premium that would make the potential investor indifferent between participating in a RO scheme and abstaining from it. The non-monotonic effect of the implementation of the RO scheme on the value of the investment option has to do with the fact that, while the strike price of the RO is not binding when the investment takes place, it still constitutes an upper bound for the price of electricity. This means that, while in the short run the power plant can benefit from high prices, the strike price of the RO will be reached with a positive probability limiting the power plant's profitability.

If the electricity market is instead short at the time of the investment, i.e. if the strike price of the RO is binding when the optimal investment threshold is reached, both the timing and the value effect are shown to be ambiguous. For a given strike price, we identify three possible cases. First, there is a lower region of RO premiums for which the investment takes place later and has lower value than an investment in an *energy-only* market. In this region the combination of strike price and RO premium is such that a potential investor would choose not to participate in a RO scheme voluntarily or, alternatively, would opt for a later investment if the participation in the RO scheme is mandatory. Obviously, in this case the implementation of the RO scheme discourages investments in new capacity. Then, there is an intermediate region of RO premiums that guarantee the acceleration of the investment at the expense of the project's value. The potential investor chooses to hasten the investment in order to start cashing the RO premium early on but this is proving costly in terms of project value. Last, there is a higher region of RO premiums that have a favorable effect both on the value and on the timing of the investment. In this case the RO premium is so large that it fully neutralizes the adverse effect related to the application of the strike price of the RO.

Our paper contributes to the extant literature in two ways. First, we show that a RO scheme does not always qualify as an investment stimulus. Second, we derive the conditions under which a RO scheme can have a positive effect on the value and the timing of an investment in new capacity. We conclude the paper presenting some numerical examples focusing on the effect of the price volatility on the investment thresholds and investment option values that we derive theoretically. Our interest in the volatility of the price of electricity has to do with the fact that the *security of supply* problem is aggravated when the price of electricity is very volatile since, in that case, more capacity is needed to cope with increasing imbalances.

The rest of the paper is organized as follows. The investment problem in an electricity market without ROs is discussed in Section 2. In Section 3 we approach the same problem assuming that a RO scheme is in place. The effect of the RO scheme is discussed in Section 4. Section 5 discusses the impact of price volatility on the investment timing and the value of the investment. Conclusions follow in Section 6. All proofs are grouped in the Appendix.

2 The basic set-up and the investment problem in an energy-only electricity market

We start off discussing the problem of a potential investor who is considering entering an *energy-only* market. We subsequently approach the investment problem considering an electricity market enriched with a RO scheme which is our original contribution (Section 3).

A potential investor is contemplating investing in a power plant the size of which is normalized to one (e.g. 1 MW). We do not explicitly consider the choice of the size of the investment for two reasons. First, in the real-world applications of ROs, the SO applies a de-rating coefficient to existing and new capacity based on historical or expected availability. This standardizes the capacity and gives rise to the amount of available capacity which can then be considered a homogeneous product. ROs are issued per unit of standard (de-rated) capacity, typically, one RO per MW. The amount of issued ROs depends on the demand for capacity, which is established by the SO on the basis of the expected need to reach a predetermined target of *security of supply* (see SEM, 2016b; TERNA, 2019 for further details).[5] In this paper we do not address the issue of how many ROs are needed, i.e. how severe the *security of supply* problem is. We just evaluate the conditions under which ROs enhance *security of supply* in a market that employs this specific CRM. Therefore, we abstract from any consideration regarding the size of the installed capacity. The second reason has to do with the fact that investment in new capacity is a rather homogenous choice. In a given market, it generally takes the form of a predetermined type of technology and size. As an example, Fontini and Paloscia (2007) show that new investments in the Italian market take the form of Combined Cycle Gas Turbine plants characterized by constant economies of scale and standard size per each production unit. Therefore, the choices of the potential investors sizewise are quite limited in reality.[6]

The investment cost per unit of capacity is $I > 0$ and is paid in its entirety at the time of the investment. As soon as the investment takes place, the power produced in the power plant is sold at the unit price P_t which is assumed to be fluctuating over time according to the following geometric Brownian motion

$$\frac{dP_t}{P_t} = adt + \sigma dW_t \qquad \text{with} \qquad P_0 = P \tag{1}$$

[5] Generally, the SO sets a target of maximum number of acceptable hours of load shedding per year (called Loss of Load Expectations - LOLE), and on the basis of the load the equivalent need of capacity is derived.

[6] Irrespective of the technical constraints affecting the investment decision, in principle, potential investors can have some flexibility when it comes to the choice of capacity. Capozza and Li (1994) and Dangl (1999) among others have shown that in this case the choice of timing and capacity are not independent. While the effect of the implementation of a RO scheme on the size of new capacity deserves further work, the non-consideration of this facet of the problem here does not affect the quality of our main results.

where a is the drift, σ is the instantaneous volatility and W_t is a standard Wiener process.[7]

The production cost of electricity is assumed to be constant and equal to $c \geq 0$. Consequently, the instantaneous profit flow associated with the electricity production is $\pi_t = P_t - c$. When c is very low, as e.g. in the case of a renewable energy source (RES) plant, π_t is positive. However, when c is substantial, as e.g. in the case of a thermal plant, π_t can potentially obtain negative values. In this case the power plant manager will consider temporarily shutting down the power plant in order to avoid making losses. Here we assume that, irrespective of the sign of π_t, the power plant is not suspending operations. The motivation of this assumption is both technical and related to the real-world attributes of energy production.

The first reason that motivates our assumption has to do with technical constraints related to energy production. Irrespective of the technology of the power plant, switching between "active" and "stand-by" mode is costly. For this reason, periods during which a power plant remains operational in spite of non-positive π_t cannot be excluded. Power plants can have "no-load" costs, i.e. quasi-fixed costs that power producers need to pay if they keep running at zero output (Kirschen and Strbac, 2004; Creti and Fontini, 2019). This means that even if a power plant manager opts for the temporal suspension of operations, some losses might be unavoidable. Our assumption therefore can be interpreted as describing investments in technology characterized by no-load costs that are high enough to induce managers not to suspend power production even under losses.

As for the technical part, in Appendix B we show that if we allow for an operationally flexible power plant, **the associated optimal investment threshold cannot be expressed in closed form. The lack of a closed form solution deters us from using an operationally flexible power plant as our standard of comparison since the economic interpretation of the results becomes quite difficult.**[8] Nevertheless, this assumption has no effect on our results regarding the optimal investment threshold and the value of the option to invest in a power plant when a RO scheme is in place. The reason is that, as we shall see in more detail in the next section, the writer of a RO is obliged to deliver energy when called by the SO no matter if this is profitable or not. This means that a RO issuer is in any case operationally rigid.

We also assume that, i) the potential investor is risk-neutral and discounts future payoffs using the interest rate $r > a$,[9] and, ii) once launched, the project runs forever.[10] The operating value of the power plant at the generic time point t is:

$$V(P_t) = E_t\left[\int_t^{\infty} (P_s - c)\, e^{-r(s-t)} ds\right] = \frac{P_t}{r-a} - \frac{c}{r} \tag{2}$$

The potential investor has the option to invest in the power plant and get $V(P_t)$ by spending I. However, s/he is not obliged to make the decision immediately. On the contrary, s/he has the option to delay the investment decision and reconsider it at some point in the future. This ability of

[7] We deviate from models that incorporate seasonality, mean-reversion and price spikes, for three reasons. The first one has to do with the practical implementation of ROs. In all the electricity markets that employ them, ROs cover spans of several years. Thus, the presence of daily or weekly spikes and seasonalities can be neglected in the long run. This can be justified if we interpret the price P_t as, e.g. a weekly average price (see Bosco et al., 2010 and Gianfreda et al., 2016). The second reason is mathematical tractability. A mean-reverting process would lead to similar results but at the cost of a much higher mathematical sophistication and of the lack of explicit solutions. Finally, the mean-reversion effect in electricity prices is not unanimously recognized. For example, de Vany and Walls (1999) find unit roots (i.e. random-walk-like dynamics) in U.S. markets, and Bosco et al. (2010) reach the same result for several European markets. In fact, Bosco et al. (2010) even claim that previous findings suggesting mean-reversion could be due to the use of non-robust statistical techniques.

[8] **See Appendix B for further details.**

[9] This is a standard assumption. See e.g. Dixit and Pindyck (1994, p. 138).

[10] In principle power plants remain active for long periods of time that can be approximated as infinitely long. See e.g. Dahlgren and Leung (2015).

the potential investor to delay the investment affects profoundly her/his decision to invest. In fact, according to the real options approach, the investment takes place only as soon as the expected payoff exceeds the investment cost by a wedge equal to the value of the option to further postpone the investment decision. Furthermore, since at any time t all the information about the future evolution of the stochastic process (1) is embodied in P_t, there exists an optimal investment rule of the form: "invest immediately if P_t is at, or above, a critical threshold and wait otherwise" (see e.g. McDonald and Siegel, 1986).

In order to derive the optimal investment threshold, we first need to explicitly determine the value of the option to invest in the power plant. At $t = 0$ the option value is equal to

$$F(P) = \sup_{\tau} E_0 \left[e^{-r\tau} \left(V \left(P_\tau \right) - I \right) \right] \tag{3}$$

where the supremum is taken over all the stopping times τ and the optimal stopping time is of the form $\tau \colon = \inf \left\{ t > 0 | \, P_t \geq \tilde{P} \right\}$. The difference $V\left(P_t\right) - I$ is the net operating value of the power plant at the generic time point t, i.e. the termination value of the project. The termination value is associated with the variational inequality:

$$\max \left(\frac{1}{2} \sigma^2 P^2 F_{PP} + aPF_P - rF, V - I - F \right) = 0 \tag{4}$$

Assuming that the initial market price is sufficiently small so that investing immediately is not preferable,[11] Ineq. (4) reduces to:

$$\frac{1}{2} \sigma^2 P^2 F_{PP} + aPF_P - rF = 0 \tag{5}$$

subject to:

$$F(0) = 0 \tag{6}$$

$$F(\tilde{P}) = \frac{\tilde{P}}{r - a} - \frac{c}{r} - I \tag{7}$$

$$F'(\tilde{P}) = \frac{1}{r - a} \tag{8}$$

Condition (6) arises from the observation that if the price goes to zero, then the operating value of the power plant becomes negative. Consequently, the value of the option to invest should be equal to zero as waiting forever would be optimal. Conditions (7) and (8) come from the consideration of the optimal investment threshold $\tilde{P}$. Condition (7) is the value matching condition and implies that as soon as the potential investor decides to exercise the investment option s/he will receive exactly the termination value $\frac{\tilde{P}}{r-a} - \frac{c}{r} - I$. Finally, Eq. (8) is a standard smooth pasting condition.

Solving Eq. (5) we obtain $F\left(P_t\right) = \Theta_1 P_t^{\beta_1} + \Theta_2 P_t^{\beta_2}$ where $\beta_{1,2} = \frac{1}{2} - \frac{a}{\sigma^2} \pm \sqrt{\left(\frac{a}{\sigma^2} - \frac{1}{2} \right)^2 + \frac{2r}{\sigma^2}}$ with $\beta_1 > 1$, $\beta_2 < 0$. From Eq. (6), the second constant term is equal to zero ($\Theta_2 = 0$) whereas from Eqs. (7) and (8) we obtain

$$\tilde{P} = \frac{\beta_1}{\beta_1 - 1} \left(r - a \right) \left(\frac{c}{r} + I \right) \tag{9}$$

and $\Theta_1 = \frac{\frac{\tilde{P}}{r-a} - \frac{c}{r} - I}{\tilde{P}^{\beta_1}}$.

[11] Otherwise our problem reduces to the mere maximization of the net present value $V\left(P_t\right) - I$.

Summing up, the value of the option to invest is:

$$F(P) = \left(\frac{\tilde{P}}{r-a} - \frac{c}{r} - I \right) \left(\frac{P}{\tilde{P}} \right)^{\beta_1} \tag{10}$$

From Eq. (9) and Eq. (10) we obtain $F(P) = \frac{1}{\beta_1 - 1} \left(\frac{c}{r} + I \right) \left(\frac{P}{\tilde{P}} \right)^{\beta_1}$ the positivity of which guarantees that the potential investor will indeed perform the investment as soon as $\tilde{P}$ is reached. The expressions for $\tilde{P}$ and $F(P)$ are standard in the real options literature (see Dixit and Pindyck, 1994) and will serve as our benchmark values.

3 The investment problem in the presence of a RO scheme

Contrarily to the investment scenario discussed in the previous section we now assume that a RO scheme is in place. A schematic presentation of such a scheme is provided in Figure 1. In an *energy-only* electricity market (left panel), the power plant makes profits whenever $P_t > c$. If instead the power plant sells ROs to the SO (right panel), the RO seller cashes ex-ante the premium m. In principle, the premium m can be paid in full ex-ante, i.e. before the delivery period, or calculated and delivered through periodic installments. Without loss of generality here we assume the latter.[12]

The RO is also capping the price, and therefore the revenues, that the power plant gains from selling electricity to the market. In the following, K is the predetermined strike price of the RO. In competitive power markets, the price of electricity corresponds to the marginal cost of the marginal plant, i.e. the plant that is called to produce the last unit of electricity at a given time. In the RO scheme, the strike price is set at the level of the marginal cost of an efficient peak plant (TERNA, 2019).[13] Hence, in the case where K is not binding at the time when the RO is issued, we are dealing with an electricity system that has enough capacity. On the contrary, in the case where K is binding, the electricity system is short in capacity since some less efficient peaker is producing.[14]

Figure 1 about here

Figure 1: *The RO scheme. The left panel refers to an energy-only market. The power plant makes profits whenever $P_t > c$ (grey area). The right panel refers to an electricity market with ROs. By selling a RO the power plant receives the premium m. At the same time, the RO sets an upper bound to the price of electricity since, whenever $P_t > K$, the power plant needs to return to the SO the difference $P_t - K$.*

Note that in a first-best world, the premium m would be given by the expected discounted value of the future implicit penalties, i.e. the flow of foregone revenues

[12]For instance, in the Forward Capacity Market of the ISO-New England and in the new Italian RO scheme the premium will be paid in monthly installments. Note that m should not be treated as an investment subsidy paid by the SO to the power producers since, by paying m, the SO obtains the right to exercise the RO. For details on investment subsidization see e.g. Grossman et al. (2013).

[13]An efficient peak plant is a power plant that, among those producing with the peak technology, does so at the lowest cost.

[14]Note that K is not a reflecting barrier for the price of electricity. For details on price ceilings, reflecting barriers and their properties see Ch. 9 in Dixit and Pindyck (1994) and Roques and Savva (2009).

that power producers will have to return to the SO in exchange for cashing in the premium:

$$E_0\left[\int_\tau^\infty m e^{-rt}dt\right] = E_0\left[\int_\tau^\infty \max\left(P_t - K, 0\right)e^{-rt}dt\right]$$

However, in real-world settings, this need not be the case. ROs are peculiar products that are exchanged in markets that are quite different from financial ones. Exchanges occur in specific periods or dates, trading is less frequent and less liquid than for standard financial products and contingent to the occurrence of specific events (typically when a problem of security of supply occurs or is foreseen). Moreover, ROs are often sold through auction mechanisms that can be plagued by design failures.[15] Auction participants can exert market power or face uncertainties that can be difficult to hedge. Moreover, by adopting ROs the SO sees its own financial structure affected, since the RO premium is accounted for as a cost in the SO's book and the implicit penalties are revenues that will be earned in the future. Thus the financial targets of the SO might not align with the level of the premium that delivers the desired level of security of supply. For these reasons, the premium m can take several possible values and not just the expected discounted value of the implicit penalties.

A RO has also a physical element since it obliges the installed capacity to be available whenever it is required. In this respect, the SO sets *explicit penalties* for non-compliance that discourage strategic behavior on the power plants' side such as the non delivery of the energy as specified in the RO. Consequently, the participation in a RO scheme makes a power plant operationally rigid. In the following, we assume that *explicit penalties* are so high that the power plant has no choice but to deliver the energy generated by the agreed capacity.

The instantaneous profit flow associated with electricity production under a RO scheme is:

$$\overline{\pi}_t = \min\left\{P_t, K\right\} - (c - m) \tag{11}$$

$$= \begin{cases} P_t - n & \text{for } P_t \leq K \\ K - n & \text{for } P_t > K \end{cases} \tag{12}$$

where $n = c - m$.[16]

Given $\overline{\pi}_t$, we can derive the power plant's operating value when a RO scheme is in place:

Proposition 1 *The operating value of the power plant when a RO scheme is in place is*

$$\overline{V}\left(P_t\right) = E_t\left[\int_t^\infty \overline{\pi}_s e^{-r(s-t)}ds\right] = \begin{cases} AP_t^{\beta_1} + \frac{P_t}{r-a} - \frac{n}{r} & \text{for } P_t \leq K \\ BP_t^{\beta_2} + \frac{K-n}{r} & \text{for } P_t > K \end{cases} \tag{13}$$

where

$$A = -\frac{r - \beta_2 a}{(r-a)\left(\beta_1 - \beta_2\right)r}K^{1-\beta_1} < 0 \tag{14}$$

$$B = -\frac{r - \beta_1 a}{(r-a)\left(\beta_1 - \beta_2\right)r}K^{1-\beta_2} < 0 \tag{15}$$

[15] For instance, in the Italian RO auction of November 2019, all the auctions cleared at their price cap regardless of the bidding behavior of the participants (see TERNA, 2019a, 2019b).

[16] In principle, n can be either positive or negative. It will be positive for all those power plants that have large operating costs, and in all those cases in which the periodic installment m is not large enough to overtake the marginal cost of production. It will be negative for those power plants that use renewable energy sources and consequently have negligible marginal costs.

Proof. In the Appendix. ■

The terms $AP_t^{\beta_1}$ and $BP_t^{\beta_2}$ represent the obligation of the power plant to cash K when $P_t > K$, and P_t otherwise ($P_t \leq K$). Note that the constants A and B are both negative denoting that these obligations are, by definition, reducing the operating value of the power plant.

In Eq. (13) we observe that for $P_t \leq K$, the operating value of the power plant is given by the sum of the obligation to cash K as soon as P_t becomes larger than K, $AP_t^{\beta_1}$, plus the net present value associated with electricity production, $\frac{P_t}{r-a} - \frac{n}{r}$. Note that $AP_t^{\beta_1}$ is increasing, i.e. is becoming less costly, in K. This makes sense considering that an increase in the chosen strike price implies that P_t will reach K less frequently. In the mean time, the power plant manager will have the opportunity to benefit from high electricity prices that are however still smaller than K.

On the other branch of the value function, that is for $P_t > K$, the value of the power plant is given by the sum of the obligation to cash P_t as soon as the price falls below K, $BP_t^{\beta_2}$, plus the present value of the flow of net payments in this case, $\frac{K-n}{r}$. Note that $BP_t^{\beta_2}$ is decreasing, i.e. is becoming more costly, in K. This makes sense considering that an increase in the chosen strike price implies that the power plant will cash the maximum electricity price K less frequently.

Let us now determine the value of the option to invest. As in Eq. (3) the value of the option to invest is given by:

$$\overline{F}(P) = \sup_{\tau} E_0 \left[e^{-r\tau} \left(\overline{V}(P_\tau) - I \right) \right] \tag{16}$$

As before, this value is associated with the variational inequality

$$\max \left(\frac{1}{2}\sigma^2 P^2 \overline{F}_{PP} + aP\overline{F}_P - r\overline{F}, \overline{V} - I - \overline{F} \right) = 0 \tag{17}$$

Assuming that the initial market price P is sufficiently small so that investing at time zero is not preferable, Eq. (17) reduces to:

$$\frac{1}{2}\sigma^2 P^2 \overline{F}_{PP} + aP\overline{F}_P - r\overline{F} = 0 \tag{18}$$

Since the investment threshold can be higher or lower than K, and consequently $\overline{V}(P_t)$ can take two different analytical forms, we consider two possible cases:

1. K is larger than, or at most equal to, the optimal investment threshold or
2. K is smaller than the optimal investment threshold.

These two cases correspond to the two possible market configurations that can occur at the time of the investment, namely a market which is long (Case 1) or short (Case 2) in capacity.

3.1 Case 1: The market is long in capacity

Proposition 2 below presents the optimal investment threshold and the corresponding investment option value in the case where the market is long in capacity at the time of the investment, i.e. in the case where the strike price of the RO is not binding when the optimal investment threshold is reached.

Proposition 2 *Provided that* $K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$, *the optimal investment threshold is equal to*

$$P^* = \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right) \tag{19}$$

and the value of the option to invest is equal to

$$\overline{F}(P) = \left(AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I \right) \left(\frac{P}{P^*} \right)^{\beta_1} > 0 \tag{20}$$

Proof. In the Appendix. ■

In this case, K is large enough so that the timing decision of the potential investor is unaffected by it. Note in fact that P^* is not a function of K. Nevertheless, this does not mean that P^* is independent of changes in K since it has the form presented above only if the strike price of the RO is large enough, namely, if $K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$.[17] The optimal investment threshold might not be a function of K but is an increasing function of n, i.e. a decreasing function of m. This is to be expected since the periodic payment m encourages the potential investor to invest earlier so that s/he can start cashing m as early as possible.

Note that P^* can be written as:

$$P^* = \tilde{P} - \frac{\beta_1}{\beta_1 - 1}(r-a)\frac{m}{r} \tag{21}$$

Since $m > 0$, we have $P^* < \tilde{P}$. **This means that, when $K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$, the use of a RO scheme encourages the potential investor to enter the electricity market earlier than when the RO scheme is not in place. This finding answers partially (i.e. for the case when the market is long in capacity) to the first research question that we pose in Section 1 regarding the effect of the implementation of a RO scheme on the timing of investment in new capacity.**

The value of the option to invest $\overline{F}(P)$ is a function of both m and K. Applying the envelope theorem we obtain:

$$\frac{\partial \overline{F}(P)}{\partial n} = -\frac{1}{r}\left(\frac{P}{P^*}\right)^{\beta_1} < 0 \tag{22}$$

and,

$$\frac{\partial \overline{F}(P)}{\partial K} = \frac{\partial A}{\partial K} P^{\beta_1} > 0. \tag{23}$$

The value of the option to invest is increasing both in m and in K. A higher m suggests that the potential investor can count on a higher remuneration that is not subject to the fluctuations of P_t. This increases the value of the option to invest in the project of interest. Similarly, a higher K implies that, upon investment, the power plant will be able to benefit from periods of high prices before K is reached.

Last, one can show that:

Proposition 3 *For a given m, the strike price K^*:*

$$K^* = \left(\frac{(\beta_1 - 1)\tilde{A}P^{*\beta_1}}{\left(\frac{n}{r} + I\right) - \left(\frac{c}{r} + I\right)\left(\frac{P^*}{\tilde{P}}\right)^{\beta_1}} \right)^{\frac{1}{\beta_1 - 1}} \tag{24}$$

where $\tilde{A} = \frac{r - \beta_2 a}{(r-a)(\beta_1 - \beta_2) r}$ (> 0) and $K^* \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$, results in $\overline{F}(P) = F(P)$.

[17] Recall that, by assumption, $P^* > P$, i.e. investing at time zero is not preferable. Alternatively, this can be written as $\frac{n}{r} + I > \frac{P}{r-a}\frac{\beta_1 - 1}{\beta_1}$. Obviously, $\frac{n}{r} + I$ needs to be strictly positive. The positivity of $\frac{n}{r} + I$ guarantees also the positivity of P^*.

Proof. In the Appendix. ■

This means that despite the fact that $P^* < \tilde{P}$, the SO can keep the value of the project at $F(P)$ by choosing K^* for a given m.[18] Equivalently, any K can have the property of K^* as soon as an appropriate m^* is chosen. Summing up, the SO can, under certain conditions, use the RO scheme in order to induce earlier investment without depreciating the value of the investment option. **This finding gives a partial answer to the second research question that we pose regarding the effect of the implementation of a RO scheme on the value of the option to invest in new capacity.**

3.2 Case 2: The market is short in capacity

When $K < \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$ we can have either $K \leq Ir + n$ or $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$:

Proposition 4 *Provided that $K \leq Ir + n$, the investment does not take place.*

Proof. In the Appendix. ■

Proposition 4 refers to combinations of m and K that do not allow for the investment to take place. In these cases, the strike price of the RO is too low to remunerate for the investment and the operating cost.

For higher values of K we have:

Proposition 5 *Provided that $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$, the optimal investment threshold is equal to*

$$P^{**} = \left[\frac{1}{B}\frac{\beta_1}{\beta_1 - \beta_2}\left(I - \frac{K-n}{r}\right)\right]^{\frac{1}{\beta_2}} \tag{25}$$

and the value of the option to invest is equal to

$$\overline{F}(P) = \left(BP^{**\beta_2} + \frac{K-n}{r} - I\right)\left(\frac{P}{P^{**}}\right)^{\beta_1} > 0 \tag{26}$$

Proof. In the Appendix. ■

Contrarily to P^* which is always smaller than $\tilde{P}$, P^{**} can be larger, smaller or exactly equal to the benchmark investment threshold $\tilde{P}$. A comparison between P^{**} and $\tilde{P}$ suggests that:

Proposition 6 *For any $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$, a periodic cash flow*

$$\tilde{m} = c + rI - K + K\frac{r - \beta_1 a}{(r-a)\beta_1}\left(\frac{\tilde{P}}{K}\right)^{\beta_2} \tag{27}$$

results in $P^{**} = \tilde{P}$.

Proof. In the Appendix. ■

This means that when $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$, the use of a RO scheme has an ambiguous effect on the optimal investment threshold. This finding completes the answer to the first research question that we pose, regarding the effect of the implementation of a RO scheme on the timing of investment in new capacity.

[18] Note that, as expected, $\lim_{m \to 0} K^* = \infty$.

One can also check that

$$\frac{\partial P^{**}}{\partial K}=\left[\frac{\beta_1(r-a)r}{(r-\beta_1 a)}\right]^{\frac{1}{\beta_2}}K^{\frac{\beta_2-1}{\beta_2}}\left(\frac{K-n}{r}-I\right)^{\frac{1}{\beta_2}}\frac{1}{\beta_2}\left(\frac{\beta_2-1}{K}+\frac{1}{\left(\frac{K-n}{r}-I\right)r}\right)<0 \tag{28}$$

and

$$\frac{\partial P^{**}}{\partial n}=\frac{P^{**}}{\beta_2}\frac{1}{I-\frac{K-n}{r}}\frac{1}{r}>0. \tag{29}$$

Similarly to P^*, P^{**} is an increasing function of n, i.e. a decreasing function of m. This means that a higher level of m encourages the potential investor to invest earlier. At the same time P^{**} is, as expected, decreasing in K. This means that a high strike price K will encourage the potential investor to invest earlier. This is thanks to the fact that the potential investor will benefit from periods of high electricity prices before K is reached. On the contrary, when K is low, the potential investor will attempt to hedge against the periods during which the low strike price is binding by investing later on.

Let us now see what is the effect of K and m on the value of the option to invest. Applying the envelope theorem we obtain:

$$\frac{\partial \overline{F}(P)}{\partial n}=-\frac{1}{r}\left(\frac{P}{P^{**}}\right)^{\beta_1}<0 \tag{30}$$

and

$$\frac{\partial \overline{F}(P)}{\partial K}=-\left(\frac{P}{P^{**}}\right)^{\beta_1}\frac{\beta_2}{\beta_1-\beta_2}\left(\frac{1}{r}+\frac{\beta_1}{P^{**}}\left(I-\frac{K-n}{r}\right)\frac{\partial P^{**}}{\partial K}\right)>0 \tag{31}$$

As in Case 1, the value of the option to invest is increasing both in m and in K. A comparison between $F(P)$ and $\overline{F}(P)$ suggests that:

Proposition 7 *For a given* $K\in\left(Ir+n,\frac{\beta_1}{\beta_1-1}(r-a)\left(I+\frac{n}{r}\right)\right)$*, a periodic cash flow* m^{**} *that satisfies*

$$\left(I-\frac{K-(c-m^{**})}{r}\right)\frac{\beta_2}{\beta_1-\beta_2}=\left(\frac{c}{r}+I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m^{**})}{\tilde{P}}\right)^{\beta_1} \tag{32}$$

guarantees $F(P)=\overline{F}(P)$*.*

Proof. In the Appendix. ■

This proposition completes the answer to the second research question that we pose regarding the effect of the implementation of a RO scheme on the value of the option to invest in new capacity. Contrarily to Case 1, in Case 2 the SO can choose combinations of m and K that result either in $F(P)=\overline{F}(P)$ or in $\tilde{P}=P^{**}$. Nevertheless, for any given K we have $\tilde{m}<m^{**}$ which means that it is not possible to have the two equalities holding at the same time.[19] Summing up, the SO can, under certain conditions, use the ROs as investment stimuli either inducing earlier investment or appreciating the value of the option to invest in the power plant.

Last, note that changes in n and K affect also the conditions that allow for P^* and P^{**}. For instance we have, $\frac{\partial}{\partial n}\left[\frac{\beta_1}{\beta_1-1}(r-a)\left(I+\frac{n}{r}\right)\right]>1$. Hence, an increase in n (decrease in m) enlarges the interval $\left(Ir+n,\frac{\beta_1}{\beta_1-1}(r-a)\left(I+\frac{n}{r}\right)\right)$. At the same time, an increase in n (decrease in m) tightens the condition $\frac{\beta_1}{\beta_1-1}(r-a)\left(\frac{n}{r}+I\right)\leq K$ that allows for P^*. This means that an increase in n (decrease in m) relaxes the conditions that allow for P^{**} ($>K$) to be the optimal investment threshold and tightens the condition that allows for P^* ($\leq K$) to be the optimal one.

[19]The proof is in the Appendix.

4 Discussion

Figure 2 below summarizes our findings.

Figure 2 about here

Figure 2: *Case 1 and Case 2*

The left panel of Figure 2 refers to Case 1, that is, to an electricity market that is long in capacity. The right panel of Figure 2 instead, refers to an electricity market that is short in capacity (Case 2). In Case 1, the implementation of a RO scheme favours, in expected terms, earlier investment (Eq. (21)). On the contrary, the effect on the value of the investment option is ambiguous. If producers are free to decide whether to participate in the RO scheme or not, they would do so only if, for a given strike price K, m is large enough, namely, larger than m^* (Proposition 3).

When instead the electricity market is short in capacity (Case 2) both the timing and the value effect are ambiguous (see Propositions 6 and 7 respectively). When, for a given K, $m > m^{**}$, the RO scheme favours investments of higher value that take place, in expected terms, earlier than in an *energy-only* market. When, $m \in (\tilde{m}, m^{**})$ the timing effect is still the same but the value effect is reversed. This implies that under a RO scheme in which participation is voluntary, a potential investor would abstain from participating in the scheme. Last, for $m < \tilde{m}$, also the timing effect is reversed.

It is clear that the effect of a RO scheme on the timing **(first research question)** and the value of an investment **(second research question)** depends on whether participation in such a scheme is voluntary for a power producer or not. In some real-world cases, such as the ISO-New England for instance, the participation to the RO scheme is mandatory.[20] In this case, our results suggest that it is possible that a RO scheme discourages investments in power production. At the same time, there exist energy markets in which new investors are free to decide whether to participate in the RO scheme or not. For instance, in Italy a power producer has no obligation to sell ROs to the SO. This means that no investor would voluntarily choose to sell ROs if this is expected to be non-profitable.

Another consequence of our findings refers to the technological neutrality of ROs. In principle, one can distinguish the different types of investment by looking at the relative amount of their fixed and variable costs. Consider for instance a power plant producing electricity from a conventional primary energy source (such as a gas-fired power plant) and a plant producing electricity from RES. The former is typically characterized by high operational and low investment costs. On the contrary, the latter has low operational and high investment costs. In our model, a power plant using conventional energy sources would be characterized by a high c and a low I whereas a power plant using RES would have a low c and a high I. Nevertheless, throughout our analysis we only come across the total investment cost $I + \frac{c}{r}$ which means that as soon as the total cost $I + \frac{c}{r}$ remains fixed, the results will remain unaffected. In other words, the RO scheme does not favor one type of technology over another.

[20] In the Forward Capacity Market (FCM) participation is mandatory for existing capacity. Power producers can call for a temporary exemption of their obligation if they do not intend to participate in the market. New capacity can voluntarily be qualified to participate in the FCM auctions prior to completion of the investment. It would be regarded as existing and be mandated to participate in the FCM auctions once the investment project is competed and the capacity ready to supply energy. For further details, see https://www.iso-ne.com.

Last, as far as the net present value of the RO scheme is concerned, in the Appendix we show that since the instantaneous savings for the SO are of the form $s_t = \max\{P_t - K, 0\}$, the net present value of employing a RO scheme is:

$$\underline{V}(P_t) = \begin{cases} -AP_t^{\beta_1} - \frac{m}{r} & \text{for } P_t \le K \\ -BP_t^{\beta_2} + \frac{P_t}{r-a} - \frac{K}{r} - \frac{m}{r} & \text{for } P_t > K \end{cases} \tag{33}$$

We also have $\underline{V}(P_t) = V(P_t) - \overline{V}(P_t)$, $\partial\underline{V}(P_t)/\partial m < 0$ and $\partial\underline{V}(P_t)/\partial K < 0$. The equality $\underline{V}(P_t) + \overline{V}(P_t) = V(P_t)$ needs to hold as long as the RO is a contract between the SO and the power plant that leaves the economic fundamentals of the investment (e.g. investment cost, operating cost, stochastic process related to the price etc.) unchanged. As for the signs of $\partial\underline{V}(P_t)/\partial m$ and $\partial\underline{V}(P_t)/\partial K$, an increase in m implies a more costly policy and an increase in K implies that the SO will benefit from the RO less frequently.

5 The effect of price volatility on the investment

In this section we discuss how the timing, the net present value (NPV) and the value of the option to invest are affected by different levels of price volatility. Several scholars (Woo et al., 2011; Ketterer, 2014; Higgs et al., 2015; Brancucci et al., 2016; Pereira da Silva and Horta, 2019) have argued that the increase of electricity production from RES causes, i) the reduction of the average electricity price and, ii) the increase of its volatility.[21] The first effect is expected to result in reduced revenues and, consequently, is expected to discourage investments in back-up power plants, i.e. power plants that can quickly ramp-up and down complementing power plants using non-controllable RES for electricity production. At the same time, the increase in volatility makes the problem of *security of supply* even more relevant since it might increase the frequency with which such a flexible capacity is needed. Given all this, it is evident that a discussion on the relationship between price volatility and the ROs' ability to stimulate investments is of particular interest for those systems that are experiencing an increase in the share of power plants that produce electricity using non-controllable RES.

Let us assume the following reference values for the parameters of the model (unit measures are between parentheses): $a = 0$, $r = 0.000005$, $c = 25$ (Euros/MWh), $I = 2000000$ (Euros/MW) and $P = 0.1$ (Euros/MWh). Then, for $\sigma \in [0.0034, 0.0051]$, $K = 200$ (Euros/MWh) and $m = 25$ (Euros/MWh) we obtain a solution that corresponds to Case 1 (see Figure 3).[22]

Figure 3 about here

[21] However, other scholars have argued that the evidence is not univocal and the effect on volatility might differ depending on the different types of RES, the markets and prices considered, the time spell and the way volatility is measured. See Rintamäki et al. (2017) and Khoshrou et al. (2019).

[22] The values for investment and operational costs refer to an efficient new gas-fired plant (EIA, 2020). For the structural parameters of the stochastic process capturing the evolution of the price of electricity as well as the values of the strike price and the premium we refer to the Italian market (Andreis et al. 2020). **In particular, σ is the hourly rate that corresponds to an average yearly volatility that ranges from 0.26 to 0.53. These figures are consistent with the yearly volatility of weekly-averaged day-ahead prices for the Italian continental price zones (data is available from the authors upon request). For the drift parameter a, day-ahead prices for the Italian continental price zones suggest that a suitable value could be $a = 0$ (which of course does not change when changing time scale). Finally,** r is the hourly rate that corresponds to a yearly average risk-adjusted market rate of 4.4% (EIA, 2020). Note that P, the starting price, is kept low just to make sure that the optimal investment threshold lies somewhere in the future.

Figure 3: *Investment thresholds, NPVs and Option values in Case 1*

The left panel shows the optimal investment thresholds P^* and $\tilde{P}$, the chosen strike price K and the strike price that would result in $\overline{F} = F$, K^*. The right panel shows the investment option values, $\overline{F}$ and F, and their corresponding NPVs. Since the $\overline{NPV}$ and NPV are computed by scaling up $\overline{F}$ and F by $\left(\frac{P^*}{P}\right)^{\beta_1}$ and $\left(\frac{\tilde{P}}{P}\right)^{\beta_1}$ respectively, we use a secondary vertical axis in order to plot all four curves in the same figure. We do the same for Figures 4 and 5 below.

As expected, higher levels of volatility correspond to higher investment triggers and higher investment option values. This finding is standard in the real options literature. Note also that $\overline{F}$ is flatter than F. This is attributed to the fact that the RO scheme imposes the strike price K while paying the premium m. For low levels of volatility we have $\overline{F} > F$ because the positive effect of cashing the option premium is stronger than the negative effect of having to respect K. On the contrary, for high levels of volatility we have $\overline{F} < F$ since the adverse effect dominates. Hence, while a power producer will voluntarily participate in the RO scheme for low levels of volatility, s/he will abstain from participating in the RO scheme when σ becomes higher than 0,00425. At this level of σ the combination of strike price and premium guarantees $\overline{F} = F$. As for the effect of volatility on the NPV of the power plant at the time of the investment, in an *energy-only* market higher volatility implies a higher investment threshold and consequently a higher value for the power plant at the time of the investment. However, in an electricity market that employs ROs this effect dissipates since the power producer will be unable to benefit from P_t above K.

For $\sigma \in [0.0039, 0.0056]$, $K = 100$ and $m = 2.5$ we obtain a solution that corresponds to Case 2 (see Figure 4).

Figure 4 about here

Figure 4: *Investment thresholds, NPVs and Option values in Case 2 under* $m < m^{\star\star}$

Obviously, in Figure 4 we are dealing with a case of low value $\left(\overline{F} < F\right)$ and ambiguous timing. This means that for $\sigma \in [0.0039, 0.0056]$ and $K = 100$, the RO premium $m = 2.5$ is smaller than m^{**} and becomes equal to $\widetilde{m}$ when σ is about 0.0048. In this case, the participation of a power producer in the RO scheme makes her/him worse off both in terms of NPV at the time of the investment and in terms of investment option value. For $\sigma \in [0.0028, 0.0036]$, $K = 1.9$ and $m = 34$ we obtain again a solution that corresponds to Case 2 but this time we have an ambiguous effect on the value of the option to invest and always earlier investment (see Figure 5).

Figure 5 about here

Figure 5: *Investment thresholds, NPVs and Option values in Case 2 under* $m > \widetilde{m}$

In this case the option premium $m = 34$ is larger than $\widetilde{m}$ and is reaching m^{**} when σ is about 0.0032. For $\sigma < 0.0032$ we have $\overline{F} > F$ because the positive effect of cashing the option premium is stronger than the negative effect of having to respect the strike price K. On the contrary, for higher levels of volatility we have $\overline{F} < F$ since the adverse effect prevails. Hence, for some levels of volatility the power producer opts for participating in the RO scheme. However, this is not true for the whole range of values.

The figures suggest that while the investment triggers remain monotonic in volatility, the value of the option to invest is concave in σ. The concavity of $\overline{F}$ with respect to σ is attributed to the fact that the effect of the components of the RO scheme, i.e. the RO premium and the *implicit penalty*, on the value of the investment option depends on the level of price volatility. For low σ the application of the RO scheme benefits the power plant manager since, on one hand, s/he cashes the RO premium and, on the other, s/he rarely pays the *implicit penalty* to the SO as price spikes are infrequent. For high σ the application of the RO scheme has the opposite effect since the RO premium cannot remunerate the power plant manager for the more frequent payment of the *implicit penalty*.

6 Conclusion

In this paper we study the conditions under which a RO scheme can induce investments in power production. The literature on CRMs describes ROs as tools that can be used to enhance *security of supply*, stimulating the adoption of new capacity. Nevertheless, our results cast some doubts on the effectiveness of ROs as investment stimuli.

In the Introduction we pose two research questions: "How does the use of a RO scheme affect the timing of investments in new capacity?" and "What is the effect of the implementation of this scheme on the value of the option to make such an investment?". Our findings suggest that the adoption of a RO scheme can potentially hinder the *security of supply* by delaying the adoption of new capacity. We also show that a RO scheme can adversely affect the value of the option to invest in power production.

If the electricity market is long in capacity at the time of the investment, then this takes place, in expected terms, earlier than in an *energy-only* market. Nevertheless, the investors are not necessarily better off since the value of the option to invest depends also on the magnitude of the premium that the RO pays to its issuer. If instead the electricity market is short in capacity at the time of the investment, then both the timing and the value effect are ambiguous. While there are combinations of the strike price and the RO premium that raise the investment option value and hasten its exercise, there are also combinations that have the opposite effect both in terms of value and in terms of timing.

The duration of the obligation set by the RO is an area of research that deserves future work; we have not tackled it here. In order to perform our analysis, we adopted the simplifying assumption of a life-long lasting investment and RO. In reality, this is not necessarily the case. There are RO schemes, such as the Italian one (TERNA, 2019), in which the obligation set by the RO on the power producer lasts for a period that is quite long (15 years). In this case, our assumption can be regarded as not too restrictive. However, when the obligation set by the RO is short, for example one year as is the case in the ISO-New England, the analysis cannot abstain from taking this into consideration.

Another issue that we do not consider here is the relationship between the premium and the strike price of the RO. As we mentioned in Section 3, from a theoretical point of view, the premium corresponds to the expected discounted value (under some risk-adjusted measure) of the flow of the *implicit penalties*, i.e. the flow of money that the RO issuers need to return to the SO over time.[23] However, in the real world, ROs are exchanged through procurement mechanisms that could be subject to market failures or allocative inefficiencies. In this paper we chose to treat both K and

[23] See Andreis et al. (2020).

m as parameters. Nevertheless, a careful consideration of the auction mechanism complementing a RO scheme can provide a deeper insight into this scheme's strengths and weaknesses.

The main message of this paper is that it is not correct to draw the conclusion that a RO scheme will necessarily encourage investments in new capacity. Instead, the careful implementation of this scheme proves to be crucial for its success. In this respect, the rigorous analysis of the objectives of the responsible policy maker is needed. One direction in which this work could be extended is to model explicitly a policy maker who chooses to employ a RO scheme because this proves to be optimal in terms of social welfare (see, e.g. Huisman and Kort, 2015). This will allow for the proper identification of the optimal strike price of the ROs, the optimal design of the auction mechanism through which ROs are exchanged, their duration and generally all the parameters that need to be correctly adjusted so that the RO scheme can be successfully implemented.

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A Appendix

A.1 Proof of Proposition 1

The firm's operating value, $\overline{V}(P_t)$, satisfies the following differential equation:

$$\Gamma\overline{V}^L(P_t) = -(P_t - n) \text{ for } P_t \leq K \tag{A.1}$$

$$\Gamma\overline{V}^H(P_t) = -(K - n) \text{ for } P_t > K \tag{A.2}$$

where:

$$\Gamma = -r + aP_t\frac{\partial}{\partial P_t} + \frac{1}{2}\sigma^2 P_t^2 \frac{\partial^2}{\partial P_t^2} \tag{A.3}$$

$\overline{V}^L(P_t)$ is the firm's operating value under $P_t \leq K$ and $\overline{V}^H(P_t)$ is the firm's operating value under $P_t > K$.

Solving we obtain:

$$\overline{V}^L(P_t) = AP_t^{\beta_1} + CP_t^{\beta_2} + \frac{P_t}{r-a} - \frac{n}{r} \tag{A.4}$$

$$\overline{V}^H(P_t) = DP_t^{\beta_1} + BP_t^{\beta_2} + \frac{K-n}{r} \tag{A.5}$$

The terms $\frac{P_t}{r-a} - \frac{n}{r}$ for $P_t \leq K$ and $\frac{K-n}{r}$ for $P_t > K$, capture the net value of the project. On the contrary, the sums $AP_t^{\beta_1} + CP_t^{\beta_2}$ for $P_t \leq K$ and $DP_t^{\beta_1} + BP_t^{\beta_2}$ for $P_t > K$, correspond to the obligation that the power plant undertakes when writing a RO.

Note that $\overline{V}^L(P_t)$ explodes as $P_t \to 0$ unless $C = 0$. Also note that if $P_t \to \infty$, the obligation $DP_t^{\beta_1} + BP_t^{\beta_2}$ should be valueless and this implies $D = 0$. Summing up, we have:

$$\overline{V}^L(P_t) = AP_t^{\beta_1} + \frac{P_t}{r-a} - \frac{n}{r} \tag{A.6}$$

$$\overline{V}^H(P_t) = BP_t^{\beta_2} + \frac{K-n}{r} \tag{A.7}$$

At $P_t = K$, the value matching and smooth pasting conditions require:

$$AK^{\beta_1} + \frac{K}{r-a} - \frac{n}{r} = BK^{\beta_2} + \frac{K-n}{r} \tag{A.8}$$

$$A\beta_1 K^{\beta_1 - 1} + \frac{1}{r-a} = B\beta_2 K^{\beta_2 - 1} \tag{A.9}$$

Solving we obtain:

$$A = -\frac{r - \beta_2 a}{(r-a)(\beta_1 - \beta_2) r} K^{1-\beta_1} \tag{A.10}$$

$$B = -\frac{r - \beta_1 a}{(r-a)(\beta_1 - \beta_2) r} K^{1-\beta_2} \tag{A.11}$$

Since $r > a$, the signs of A and B are determined by the signs of $r - \beta_2 a$ and $r - \beta_1 a$ respectively. From the negativity of β_2 we have $r - \beta_2 a > 0$ which results in $A < 0$. As for the sign of $r - \beta_1 a$, this can be shown to be positive in the following way. β_1 and β_2 are the roots of the characteristic quadratic $0.5\sigma^2\beta(\beta-1) + \alpha\beta - r = 0$. Plugging r/α in $0.5\sigma^2\beta(\beta-1) + \alpha\beta - r$ we obtain $0.5\sigma^2\frac{r}{\alpha}\frac{r-\alpha}{\alpha}$ which is positive. This means that r/α must be larger than the positive root β_1, i.e. $r/\alpha > \beta_1$ which means that $B < 0$.

A.2 Proof of Propositions 2 and 3

We need to solve the equation $\frac{1}{2}\sigma^2 P^2 \overline{F}_{PP} + aP\overline{F}_P - r\overline{F} = 0$ keeping in mind that the investment threshold P^* is smaller than, or at most equal to, K. Assuming a general solution $\overline{F}(P) = \Omega_1 P^{\beta_1} + \Omega_2 P^{\beta_2}$ and using the first branch of Eq. (13), we have:

$$\overline{F}(0) = 0 \tag{A.12}$$

$$\overline{F}(P^*) = AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I \tag{A.13}$$

$$\overline{F}'(P^*) = A\beta_1 P^{*\beta_1 - 1} + \frac{1}{r-a} \tag{A.14}$$

From $\overline{F}(0) = 0$ we have $\Omega_2 = 0$. Then the value matching and smooth pasting conditions give:

$$P^* = \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right) \tag{A.15}$$

and

$$\Omega_1 = \frac{AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I}{P^{*\beta_1}} \tag{A.16}$$

Note that for $P^*\,(\geq P > 0)$ to make sense we require $\frac{n}{r} + I > 0$, i.e. $\frac{c}{r} + I > \frac{m}{r}$. If on the contrary $\frac{c}{r} + I \leq \frac{m}{r}$, the periodic flow m fully covers the investment and operation cost of the project. In this case the potential investor enters the electricity market as soon as possible in order to cash the deterministic flow of m and the timing decision problem becomes trivial.

Summing up, we have:

$$\overline{F}(P) = \left(AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I\right)\left(\frac{P}{P^*}\right)^{\beta_1} \tag{A.17}$$

Note that by assumption the investment threshold P^* is smaller than, or at most equal to, K. For this to hold we require:

$$K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right) \tag{A.18}$$

At the same time, the investment takes place at P^* only if the net present value of the project at the time of the investment is positive:

$$AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I > 0 \tag{A.19}$$

This in turn implies:

$$\left(\frac{K}{P^*}\right)^{\beta_1 - 1} > \beta_1 \frac{r - \beta_2 a}{(\beta_1 - \beta_2)\, r} \tag{A.20}$$

Since $\beta_1 \frac{r-\beta_2 a}{(\beta_1-\beta_2)r} < 1$, the condition $P^* \leq K$ is stricter than the condition $AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I > 0$. This means that, the solution takes the form $P^* = \frac{\beta_1}{\beta_1-1}(r-a)\left(\frac{n}{r} + I\right)$ if $K \geq \frac{\beta_1}{\beta_1-1}(r-a)\left(\frac{n}{r} + I\right)$. This concludes the proof of Proposition 2.

As for the proof of Proposition 3, we can easily derive the K that, for a given m, results in $\overline{F}(P) = F(P)$. Plugging A (Eq. (A.10)) and P^* (Eq. (A.15)) in $\overline{F}(P)$ (Eq. (A.17)) we obtain $\overline{F}(P) = \left(-\tilde{A}K^{1-\beta_1}P^{*\beta_1} + \frac{\frac{n}{r}+I}{\beta_1 - 1}\right)\left(\frac{P}{P^*}\right)^{\beta_1}$ where $\tilde{A} = \frac{r-\beta_2 a}{(r-a)(\beta_1-\beta_2)r}\,(> 0)$. Similarly, substituting $\tilde{P}$

(Eq. (9)) in $F(P)$ (Eq. (10)) we obtain $F(P) = \frac{1}{\beta_1 - 1}\left(\frac{c}{r} + I\right)\left(\frac{P}{\tilde{P}}\right)^{\beta_1}$. Equalizing the two and solving for the strike price we obtain:

$$K^* = \left(\frac{(\beta_1 - 1)\tilde{A}P^{*\beta_1}}{\left(\frac{n}{r} + I\right) - \left(\frac{c}{r} + I\right)\left(\frac{P^*}{\tilde{P}}\right)^{\beta_1}}\right)^{\frac{1}{\beta_1 - 1}}$$

A.3 Proof of Propositions 4–7

We need to solve the equation $\frac{1}{2}\sigma^2 P^2 \overline{F}_{PP} + aP\overline{F}_P - r\overline{F} = 0$ keeping in mind that the investment threshold P^{**} is larger than K. Assuming a general solution $\overline{F}(P) = \Psi_1 P^{\beta_1} + \Psi_2 P^{\beta_2}$ and using the second branch of Eq. (13), we have:

$$\overline{F}(0) = 0 \tag{A.21}$$

$$\overline{F}(P^{**}) = BP^{**\beta_2} + \frac{K - n}{r} - I \tag{A.22}$$

$$\overline{F}'(P^{**}) = B\beta_2 P^{**\beta_2 - 1} \tag{A.23}$$

Thanks to $\overline{F}(0) = 0$ we have $\Psi_2 = 0$. Then, from the value matching condition we obtain

$$\Psi_1 = \frac{1}{P^{**\beta_1}}\left(BP^{**\beta_2} + \frac{K - n}{r} - I\right) \tag{A.24}$$

whereas from the smooth pasting condition we have:

$$P^{**} = \left[\frac{1}{B}\frac{\beta_1}{\beta_1 - \beta_2}\left(I - \frac{K - n}{r}\right)\right]^{\frac{1}{\beta_2}} \tag{A.25}$$

The value of the option to invest is,

$$\overline{F}(P) = \left(BP^{**\beta_2} + \frac{K - n}{r} - I\right)\left(\frac{P}{P^{**}}\right)^{\beta_1}.$$

Let us now check under what conditions $P^{**} > K$. Plugging B in P^{**} and rearranging we obtain

$$\left[-\frac{\beta_1 (r - a) r}{K(r - \beta_1 a)}\left(I - \frac{K - n}{r}\right)\right]^{\frac{1}{\beta_2}} > 1$$

Since $\beta_2 < 0$ this inequality holds if $-\frac{\beta_1 (r-a) r}{K(r - \beta_1 a)}\left(I - \frac{K-n}{r}\right) < 1$ which results in $K < \frac{\beta_1}{\beta_1 - 1}(r - a)\left(I + \frac{n}{r}\right)$. At the same time, the investment takes place only if the net present value of the project at the time of the investment is positive. This requires $Ir + n < K$. One can easily check that $Ir + n < \frac{\beta_1}{\beta_1 - 1}(r - a)\left(I + \frac{n}{r}\right)$ which means that the interval $\left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r - a)\left(I + \frac{n}{r}\right)\right)$ is non-empty. Last, as in Case 1, P^{**} makes sense only if $\frac{n}{r} + I > 0$, i.e. $\frac{c}{r} + I > \frac{m}{r}$. This concludes the proofs of Propositions 4 and 5.

As for the proofs of Propositions 6 and 7, we can easily derive the m that, for a given K, results in $\tilde{P} = P^{**}$ (Proposition 6) and $\overline{F}(P) = F(P)$ (Proposition 7). Starting from $\tilde{P} = P^{**}$, we plug P^{**} (Eq. (A.25)) and B (Eq. (A.11)) in $\tilde{P} = P^{**}$ and obtain $\frac{K - \tilde{n}}{r} - I = K\frac{r - \beta_1 a}{r(r-a)\beta_1}\left(\frac{\tilde{P}}{K}\right)^{\beta_2}$ where

$\tilde{n} = c - \tilde{m}$. From this, we can isolate $\tilde{m}$ which is equal to $c + rI - K + K\frac{r-\beta_1 a}{(r-a)\beta_1}\left(\frac{\tilde{P}}{K}\right)^{\beta_2}$. As for the m that results in $\overline{F}(P) = F(P)$ for a given K, plugging P^{**} (Eq. (A.25)) in $\overline{F}(P)$ we obtain $\overline{F}(P) = \left(I - \frac{K-n}{r}\right)\frac{\beta_2}{\beta_1-\beta_2}\left(\frac{P}{P^{**}}\right)^{\beta_1}$. Similarly, plugging $\tilde{P}$ (Eq. (9)) in $F(P)$ (Eq. (10)) we obtain $F(P) = \left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P}{\tilde{P}}\right)^{\beta_1}$. $\overline{F}(P)$ and $F(P)$ are equal when $\left(I - \frac{K-(c-m^{**})}{r}\right)\frac{\beta_2}{\beta_1-\beta_2} = \left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m^{**})}{\tilde{P}}\right)^{\beta_1}$ which is the formula presented in Proposition 7. In the following we prove that $\tilde{m} < m^{**}$.

A.4 Proof of $\tilde{m} < m^{**}$

When $K \in \left(Ir + n, \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{n}{r}\right)\right)$, $\tilde{m}$ is such that $\tilde{P} = P^{**}$ whereas m^{**} is such that $F(P) = \overline{F}(P)$, that is, $\left(I - \frac{K-(c-m^{**})}{r}\right)\frac{\beta_2}{\beta_1-\beta_2} = \left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m^{**})}{\tilde{P}}\right)^{\beta_1}$.

Let us see how $\left(I - \frac{K-(c-m)}{r}\right)\frac{\beta_2}{\beta_1-\beta_2}$ and $\left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m)}{\tilde{P}}\right)^{\beta_1}$ are affected by changes in m.

$$\frac{\partial\left(I - \frac{K-(c-m)}{r}\right)\frac{\beta_2}{\beta_1-\beta_2}}{\partial m} = -\frac{\beta_2}{\beta_1-\beta_2}\frac{1}{r} > 0 \tag{A.26}$$

$$\frac{\partial\left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m)}{\tilde{P}}\right)^{\beta_1}}{\partial m} = \frac{\frac{c}{r} + I}{P^{**}(m)}\frac{\beta_1}{\beta_1-1}\left(\frac{P^{**}(m)}{\tilde{P}}\right)^{\beta_1}\frac{\partial P^{**}(m)}{\partial m} < 0 \tag{A.27}$$

So $\left(I - \frac{K-(c-m)}{r}\right)\frac{\beta_2}{\beta_1-\beta_2}$ is linear and increasing in m whereas$\left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(m)}{\tilde{P}}\right)^{\beta_1}$ is decreasing in m.

We have $m^{**} > \tilde{m}$ only when

$$\left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1}\left(\frac{P^{**}(\tilde{m})}{\tilde{P}}\right)^{\beta_1} > \left(I - \frac{K-(c-\tilde{m})}{r}\right)\frac{\beta_2}{\beta_1-\beta_2} \tag{A.28}$$

Now, since $P^{**}(\tilde{m}) = \tilde{P}$ we have:

$$\left(\frac{c}{r} + I\right)\frac{1}{\beta_1-1} > \left(I - \frac{K-(c-\tilde{m})}{r}\right)\frac{\beta_2}{\beta_1-\beta_2} \tag{A.29}$$

$$(Ir + c)\frac{\beta_1(\beta_2-1)}{\beta_2(\beta_1-1)} - \tilde{m} > K \tag{A.30}$$

$$k > K \tag{A.31}$$

where $k = (Ir + c)\frac{\beta_1(\beta_2-1)}{\beta_2(\beta_1-1)} - \tilde{m}$.

We need to check if any of the K that satisfy $k > K$ belong in the interval $\left(Ir + n, \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{n}{r}\right)\right)$. If $k > \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{n}{r}\right)$, then all the $K \in \left(Ir + n, \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{n}{r}\right)\right)$ result in $m^{**} > \tilde{m}$:

$$k > \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{n}{r}\right) \tag{A.32}$$

$$(Ir + c)\frac{\beta_1(\beta_2-1)}{\beta_2(\beta_1-1)} - \tilde{m} > \frac{\beta_1}{\beta_1-1}(r-a)\left(I + \frac{c-\tilde{m}}{r}\right) \tag{A.33}$$

$$\tilde{m} > \frac{\beta_1}{\beta_2}\frac{r-a\beta_2}{r-a\beta_1}(Ir + c) \tag{A.34}$$

This is always true since $\frac{\beta_1}{\beta_2}\frac{r-a\beta_2}{r-a\beta_1}(Ir+c)<0$. Consequently, all the $K \in \left(Ir+n, \frac{\beta_1}{\beta_1-1}(r-a)\left(I+\frac{n}{r}\right)\right)$ are such that $m^{**} > \tilde{m}$.

A.5 The net present value of the RO scheme

The instantaneous savings for the SO are:

$$s_t = \max\{P_t - K, 0\} \tag{A.35}$$

$$= \begin{cases} P_t - K & \text{for } P_t > K \\ 0 & \text{for } P_t \leq K \end{cases} \tag{A.36}$$

The value of the savings is:

$$\Gamma S^L(P_t) = -(P_t - K) \qquad \text{for} \qquad P_t > K, \tag{A.37}$$

$$\Gamma S^H(P_t) = 0 \qquad \text{for} \qquad P_t \leq K, \tag{A.38}$$

where

$$\Gamma = -r + aP_t\frac{\partial}{\partial P_t} + \frac{1}{2}\sigma^2 P_t^2 \frac{\partial^2}{\partial P_t^2} \tag{A.39}$$

$S^L(P_t)$ is the value of the savings under $P_t > K$ and $S^H(P_t)$ is the value of the savings under $P_t \leq K$.

For the homogenous part we assume a solution $S(P_t) = \Delta P_t^{\beta_1} + \Phi P_t^{\beta_2}$. At the same time, the expression $\frac{P_t}{r-a} - \frac{K}{r}$ is a particular solution for the differential equation under $P_t > K$.

Summing up:

$$S^L(P_t) = \Delta_1 P_t^{\beta_1} + \Phi_1 P_t^{\beta_2} + \frac{P_t}{r-a} - \frac{K}{r} \tag{A.40}$$

$$S^H(P_t) = \Delta_2 P_t^{\beta_1} + \Phi_2 P_t^{\beta_2} \tag{A.41}$$

For these to make sense we require the value of the savings to be zero when prices go to zero which means that $\Phi_2 = 0$. Also the value of the savings cannot explode for very high prices so $\Delta_1 = 0$:

Summing up we have:

$$S(P_t) = \begin{cases} \Phi_1 P_t^{\beta_2} + \frac{P_t}{r-a} - \frac{K}{r} & \text{for } P_t > K \\ \Delta_2 P_t^{\beta_1} & \text{for } P_t \leq K \end{cases} \tag{A.42}$$

Now, at $P_t = K$ the standard optimality conditions require:

$$\Phi_1 K^{\beta_2} + \frac{K}{r-a} - \frac{K}{r} = \Delta_2 K^{\beta_1} \tag{A.43}$$

$$\Phi_1 \beta_2 K^{\beta_2 - 1} + \frac{1}{r-a} = \Delta_2 \beta_1 K^{\beta_1 - 1} \tag{A.44}$$

Solving we obtain:

$$S(P_t) = \begin{cases} -AP_t^{\beta_1} & \text{for } P_t \leq K \\ -BP_t^{\beta_2} + \frac{P_t}{r-a} - \frac{K}{r} & \text{for } P_t > K \end{cases} \tag{A.45}$$

Now, the difference between the value of the savings and the cost of the policy is:

$$\underline{V}(P_t) = S(P_t) - \frac{m}{r} = \begin{cases} -AP_t^{\beta_1} - \frac{m}{r} & \text{for } P_t \leq K \\ -BP_t^{\beta_2} + \frac{P_t}{r-a} - \frac{K}{r} - \frac{m}{r} & \text{for } P_t > K \end{cases} \tag{A.46}$$

For $P_t \leq K$ we have:

$$\frac{\partial \underline{V}(P_t)}{\partial K} = -\frac{\partial A P_t^{\beta_1}}{\partial K} < 0 \tag{A.47}$$

whereas for $P_t > K$ we have:

$$\frac{\partial \underline{V}(P_t)}{\partial K} = \frac{1}{r}\left(\frac{P_t^{\beta_2}}{K^{\beta_2}}\frac{r-\beta_1 a}{r-a}\frac{1-\beta_2}{\beta_1-\beta_2} - 1\right) < 0 \tag{A.48}$$

At the same time, for any P_t, we have:

$$\frac{\partial \underline{V}(P_t)}{\partial m} = -\frac{1}{r} < 0 \tag{A.49}$$

B Appendix

B.1 The investment problem in an energy-only electricity market when the power plant is operationally flexible

Here we reframe Section 2 explicitly assuming that the power plant is operationally flexible. This means that, whenever the price of electricity falls below the unit production cost c, the power plant manager will temporarily shut down the power plant in order to avoid making losses. In this case, the instantaneous profit flow associated with electricity production is not $\pi_t = P_t - c$ but $\pi_t = \max\{P_t - c, 0\}$.

The operating value of the power plant at the generic time point t is

$$\underline{\underline{V}}(P_t) = E_t\left[\int_t^{\infty} \max\{P_s - c, 0\}\, e^{-r(s-t)} ds\right]$$

and satisfies the following differential equation:

$$\Gamma \underline{\underline{V}}^L(P_t) = 0 \qquad \text{for} \qquad P_t \leq c, \tag{A.50}$$

$$\Gamma \underline{\underline{V}}^H(P_t) = -(P_t - c) \qquad \text{for} \qquad P_t > c. \tag{A.51}$$

The differential operator Γ is given in Eq. (A.3). $\underline{\underline{V}}^L(P_t)$ is the firm's operating value under $P_t \leq c$ and $\underline{\underline{V}}^H(P_t)$ is the firm's operating value under $P_t > c$.

Solving we obtain:

$$\underline{\underline{V}}^L(P_t) = Y P_t^{\beta_1} + U P_t^{\beta_2} \tag{A.52}$$

$$\underline{\underline{V}}^H(P_t) = X P_t^{\beta_1} + Z P_t^{\beta_2} + \frac{P_t}{r-a} - \frac{c}{r} \tag{A.53}$$

The term $\frac{P_t}{r-a} - \frac{c}{r}$ is the operating value of a power plant that is not operationally flexible (see Eq. 2). On the contrary, the sums $Y P_t^{\beta_1} + U P_t^{\beta_2}$ for $P_t \leq c$ and $X P_t^{\beta_1} + Z P_t^{\beta_2}$ for $P_t > c$ correspond to the options of the power plant manager to temporarily suspend operations when $P_t \leq c$ and restart them when $P_t > c$.

The term $\underline{\underline{V}}^L(P_t)$ explodes as $P_t \to 0$ unless $U = 0$. Also, if P_t becomes very large the option to temporarily suspend operations $X P_t^{\beta_1} + Z P_t^{\beta_2}$ should be valueless and this implies $X = 0$. Summing up, we have:

$$\underline{\underline{V}}(P_t) = \begin{cases} Z P_t^{\beta_2} + \frac{P_t}{r-a} - \frac{c}{r} & \text{for } P_t \geq c \\ Y P_t^{\beta_1} & \text{for } P_t < c \end{cases} \tag{A.54}$$

The value matching and smooth pasting conditions at $P_t = c$ result in:

$$Z = \frac{r - \beta_1 a}{(r-a)(\beta_1 - \beta_2) r} c^{1-\beta_2} > 0$$
$$Y = \frac{r - \beta_2 a}{(r-a)(\beta_1 - \beta_2) r} c^{1-\beta_1} > 0$$

The expressions in the two branches of $\underline{\underline{V}}(P_t)$ have straightforward economic interpretations. In the region $P_t < c$, operations are suspended and the power plant yields no current profit flow. However, there is a positive probability that the price process will at some future time move into the region $P_t \geq c$, where operations will resume and profits will accrue. This is captured by the positive term $Y P_t^{\beta_1}$. Similarly, $Z P_t^{\beta_2}$ is the value of the option to suspend operations whenever $P_t < c$.

The potential investor has the option to invest in the power plant and get $\underline{\underline{V}}(P_t)$ by spending I. Following the presentation of Section 2, we can derive the optimal investment threshold and the value of the option to invest in the power plant. One can easily show that the potential investor will consider investing only in the region $P_t \geq c$ (see p. 190 in Dixit and Pindyck, 1994 for more details). Assuming also that the initial market price is sufficiently small so that investing immediately is not preferable, the problem that the potential investor needs to solve is as follows:

$$\Gamma \underline{\underline{F}} = 0 \tag{A.55}$$

subject to:

$$\underline{\underline{F}}(0) = 0 \tag{A.56}$$
$$\underline{\underline{F}}(\underline{\underline{P}}) = Z \underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I \tag{A.57}$$
$$\underline{\underline{F}}'(\underline{\underline{P}}) = Z \beta_2 \underline{\underline{P}}^{\beta_2 - 1} + \frac{1}{r-a} \tag{A.58}$$

where $\underline{\underline{F}}$ is the value of the opportunity to invest in a power plant with operational flexibility and $\underline{\underline{P}}$ is the optimal investment threshold.

Condition $\underline{\underline{F}}(0) = 0$ arises from the observation that if the price goes to zero, then the operating value of the power plant becomes equal to zero. Consequently, the value of the option to invest should be equal to zero as waiting forever would be optimal. Conditions (A.57) and (A.58) come from the consideration of the optimal investment threshold $\underline{\underline{P}}$. The first is the value matching condition and implies that, as soon as the potential investor decides to exercise the investment option, s/he will receive exactly the termination value $Z\underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I$. The second is a standard smooth pasting condition. Solving the differential equation (A.55) we obtain $\underline{\underline{F}}(P_t) = \underline{\underline{\Theta}}_1 P_t^{\beta_1} + \underline{\underline{\Theta}}_2 P_t^{\beta_2}$. From $\underline{\underline{F}}(0) = 0$, we have $\underline{\underline{\Theta}}_2 = 0$ whereas from the value matching and the smooth pasting conditions we can solve for $\underline{\underline{\Theta}}_1$, which is equal to $\left(Z\underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I\right)/\underline{\underline{P}}^{\beta_1}$, and $\underline{\underline{P}}$ which **is the unique solution of** $G(\underline{\underline{P}}) = 0$ **such that** $\underline{\underline{P}} > c$**, where** G **is defined as**:

$$G(p) := Z(\beta_1 - \beta_2) p^{\beta_2} + (\beta_1 - 1)\frac{p}{r-a} - \beta_1 \left(\frac{c}{r} + I\right) \tag{A.59}$$

The function G **is convex and** $\lim_{p\to 0} G(p) = \lim_{p\to+\infty} G(p) = +\infty$, $G(\tilde{P}) > 0$, $G(c) < 0$ **and** $G(c+rI) < 0$ **where** $c+rI$ **is the Marshallian full cost. Then, the optimal investment threshold (larger than the Marshallian full cost) must lie in the increasing part of** G**,**

i.e. $G'\left(\underline{\underline{P}}\right) > 0$. From $\tilde{P} > c + rI$, $G\left(\tilde{P}\right) > 0$, and $G\left(\underline{\underline{P}}\right) = 0$ we infer that $\tilde{P} > \underline{\underline{P}}$, that is, the investment threshold corresponding to an operationally flexible plant is lower than the one corresponding to an operationally rigid one.[24] This is to be expected, since a potential investor will be willing to invest earlier in an investment project characterized by operational flexibility, as the one presented here, than in an identical investment project without operational flexibility, as the one presented in the main body of the paper.

Let us now check how $\underline{\underline{P}}$ and P^* compare. One can easily show that, provided that $K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$, an $\underline{\underline{m}}^*$ satisfying

$$\left(\frac{\beta_1 (r-a)}{c}\right)^{\beta_2 - 1} \left(\frac{\frac{c - \underline{\underline{m}}^*}{r} + I}{\beta_1 - 1}\right)^{\beta_2} = \frac{\underline{\underline{m}}^*}{r - \beta_1 a} \tag{A.60}$$

results in $P^* = \underline{\underline{P}}$.

Similarly, one can show that, provided that $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$, an $\underline{\underline{m}}^{**}$ satisfying

$$P^{**}\left(\underline{\underline{m}}^{**}\right) = \tilde{P} + \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{c}{K}\right)^{1-\beta_2}\left(I - \frac{K - \left(c - \underline{\underline{m}}^{**}\right)}{r}\right) \tag{A.61}$$

results in $P^{**} = \underline{\underline{P}}$.

As is obvious from Eqs. (A.60) and (A.61) the lack of a closed form solution for $\underline{\underline{P}}$ makes the analysis of the properties of $\underline{\underline{m}}^*$ and $\underline{\underline{m}}^{**}$ quite difficult.

B.2 Comparison between $\underline{\underline{F}}(P)$ and $\overline{F}(P)$

The value of the option to invest in an operationally flexible power plant is:

$$\underline{\underline{F}}(P) = \left(Z\underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I\right)\left(\frac{P}{\underline{\underline{P}}}\right)^{\beta_1} \tag{A.62}$$

In Case 1 where $K \geq \frac{\beta_1}{\beta_1 - 1}(r-a)\left(\frac{n}{r} + I\right)$ the value of the option to invest is:

$$\overline{F}(P) = \left(AP^{*\beta_1} + \frac{P^*}{r-a} - \frac{n}{r} - I\right)\left(\frac{P}{P^*}\right)^{\beta_1} \tag{A.63}$$

For a given m, the strike price $\underline{K}^*$:

$$\underline{K}^* = \left(\frac{(\beta_1 - 1)\tilde{A}P^{*\beta_1}}{\frac{n}{r} + I - (\beta_1 - 1)\underline{\underline{F}}(P)\left(\frac{P^*}{P}\right)^{\beta_1}}\right)^{\frac{1}{\beta_1 - 1}} \tag{A.64}$$

results in $\overline{F}(P) = \underline{\underline{F}}(P)$. Equivalently, any K can have the property of $\underline{K}^*$ as long as an appropriate $\underline{m}^*$ is chosen.

For $\underline{m}^* = \underline{\underline{m}}^*$, i.e. for $P^* = \underline{\underline{P}}$ and $\overline{F}(P) = \underline{\underline{F}}(P)$ to hold simultaneously, we require $AP^{*\beta_1} + \frac{\underline{m}^*}{r} = ZP^{*\beta_2}$. The sum on the left-hand side of the equality is comprised by

[24] **For the investment to take place at $\underline{\underline{P}}$ we require $Z\underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I > 0$ which indeed holds thanks to $G'\left(\underline{\underline{P}}\right) > 0$.**

the obligation of the plant towards the SO $\left(AP^{*\beta_1}\right)$ and the discounted flow of RO premiums $\left(\underline{\underline{m}}^*/r\right)$. On the contrary, the term on the right-hand side of the equality is the value of being operationally flexible $\left(ZP^{*\beta_2}\right)$. This equality basically says that a combination of m and K that satisfies $P^* = \underline{\underline{P}}$ will result in $\overline{F}(P) = \underline{\underline{F}}(P)$ as long as the net benefit from participating in a RO scheme exactly outweighs the loss of operational flexibility that the participation in such a scheme implies. Note that, contrarily to the benchmark presented in Section 2 where it is enough for the flow of RO premiums to cover the cost associated with the obligation to respect a certain K, here the flow of premiums needs to pay also for the forfeited flexibility that power plants not participating in the RO market enjoy.

In Case 2 where $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$ the value of the option to invest is

$$\overline{F}(P) = \left(BP^{**\beta_2} + \frac{K-n}{r} - I\right)\left(\frac{P}{P^{**}}\right)^{\beta_1} \tag{A.65}$$

For a given K, the periodic cash flow $\underline{m}^{**}$ that satisfies

$$\left(I - \frac{K - (c - \underline{m}^{**})}{r}\right)\frac{\beta_2}{\beta_1 - \beta_2} = \left(Z\underline{\underline{P}}^{\beta_2} + \frac{\underline{\underline{P}}}{r-a} - \frac{c}{r} - I\right)\left(\frac{P^{**}(\underline{m}^{**})}{\underline{\underline{P}}}\right)^{\beta_1} \tag{A.66}$$

guarantees $\overline{F}(P) = \underline{\underline{F}}(P)$.

For $\underline{m}^{**} = \underline{\underline{m}}^{**}$, i.e. for $P^{**} = \underline{\underline{P}}$ and $\overline{F}(P) = \underline{\underline{F}}(P)$ to hold simultaneously when $K \in \left(Ir + n, \frac{\beta_1}{\beta_1 - 1}(r-a)\left(I + \frac{n}{r}\right)\right)$, a necessary and sufficient condition is $BP^{**\beta_2} + \frac{K+m}{r} = ZP^{**\beta_2} + \frac{P^{**}}{r-a}$. The sum on the left-hand side of the equality captures again the net benefit from participating in a RO scheme with binding K at the time of the investment. The sum of the right-hand side instead, represents the operating value of an operationally flexible power plant abstaining from the RO market. As before, this equality implies that a combination of m and K that satisfies $P^{**} = \underline{\underline{P}}$ will result in $\overline{F}(P) = \underline{\underline{F}}(P)$ as long as the benefits from participating in a RO scheme exactly outweigh the loss of operational flexibility that the participation in such a scheme implies. The only difference with respect to the analysis presented in the main body of the paper is again the consideration of the operational flexibility that a power plant that is not selling ROs is enjoying. Again, the lack of a closed form solution for $\underline{\underline{P}}$ makes the analysis of the properties of $\underline{m}^*$ and $\underline{m}^{**}$ quite difficult.

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