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Silvia Concettini

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Silvia Concettini[1]

Universitá degli Studi di Milano and Université Paris Ouest Nanterre La Défense

Abstract

This paper studies the strategic interactions between two electricity generators, the first producing with a "traditional" technology and the second employing a "renewable" technology characterized by the random availability of capacity due to the intermittency of its power source. The competition between the "traditional" and the "renewable" power producers is examined through a modified version of the two stage *Dixit model* for entry deterrence (Dixit, 1980) with Cournot competition in the post entry stage. The outcome of the game suggests that the "renewable" generator exploits the merit order rule which governs spot electricity markets to invest and produce as if it were a sort of Stackelberg leader. While in most cases producer's preferences over strategies do not depend on the average value of capacity availability, according to the value of this parameter the market may lead to an equilibrium which benefits both the "renewable" producer and the consumers. Given that production of electricity from the renewable source depends on actual weather conditions, the analysis of ex-post payoffs reveals that "renewable" producer's preferences over strategies may be reversed for small errors in the forecasting of the true value of the average capacity availability factor when the investment cost in the renewable technology is relatively low. In this case, the incentives for strategic behaviour of the "renewable" producer may be even stronger. The main insights of the model seem to be barely sensitive to changes in the market power of competitors: even when the "renewable" generator behaves as a competitive fringe in the spot market, it is able to influence equilibrium outcome to its own advantage through investment choices although to a smaller degree than in the standard setting.

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[1]E-mail address: silvia.concettini@unimi.it

1 Introduction

Overtime a number of policy interventions contributed to reshape electricity industries worldwide. In European Union the process of liberalization was completed in 2009 with the approval of the Third Energy Package. Generation and retail activities have been opened up to competition and spot electricity markets have been created accordingly. One of the reform's goals was to boost sector's efficiency by increasing capacity adequacy and achieving technology mix optimality. The impact of liberalization on production and investments in generation has been extensively analysed within different theoretical frameworks of imperfect competition. The literature may be divided in two main strands: a first strand which investigates bidding behaviours of generators in spot electricity markets (Green and Newbery, 1992; von der Fehr and Harbord, 1993; Federico and Rahman, 2003; Fabra et al., 2006); a second one which analyzes the links between spot market design and incentives to invest in generation capacity (Murphy and Smeers, 2005; Tishler et al., 2008; Milstein and Tishler, 2009; Fabra et al., 2011).

Alongside with liberalization, European Union has approved in 2009 the Climate and Energy Package which establishes compulsory targets for limiting greenhouse gas emissions, enhancing investments in renewable technologies for power generation and improving savings from energy efficiency. A set of publicly financed measures has been put in place to reach the objective of a 20% share of EU energy consumption covered by renewable production within the 2020 time horizon. If strategic behaviours of competing generators have attracted academic attention, the study of interactions between "traditional" and "renewable" power producers remains an almost unexplored field of research (see for instance, Milstein and Tishler, 2011). Nevertheless, competition in generation seems to be substantially animated by new entrants investing in renewable technologies given that photovoltaic and wind capacities represented around the 70% of the 50 GW of new capacity built in European Union between 2010 and 2011 (Terna S.p.A., 2012).

This paper paper aims at filling this gap by proposing a model for competition in generation which takes into account the particular features of production and trade of renewable power. Concerning production, the model embeds the randomness which characterizes power generation from renewable sources such as solar and wind. The gap between installed capacity and production possibilities for renewable power plants is a non negligible economic and security issue: it changes investment preferences and influences system security.[2] Concerning trade, whereas real spot markets are organized as uniform price auctions in which firms compete in prices, in a stylized model with a "traditional" and a "renewable" power producers, firms seem rather to compete in quantities because of merit order rule. The merit order is a way of ranking available sources in ascending order of their variable costs: the electricity produced at the lowest variable cost is the first to be brought on line to meet demand, while the one generated at the highest variable cost is the last. Given that electricity from renewable sources has zero or negligible variable production costs, it is always the first to be dispatched, leaving the residual demand to the higher variable cost producer. Because of marginal pricing rule, the market price equalizes the bid submitted by the "traditional" (marginal) producer[3] and is granted to all inframarginal units as well.

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[2]In Italy for instance the combined photovoltaic and wind capacities represented around 20% of total capacity in 2012 while their production was a 10% share of total power production in the same year. In Germany photovoltaic and wind capacities represented more than 30% of total capacity in 2011 while their production was a 10% share of total power production (Terna S.p.A., 2012. See www.terna.it).

[3]We neglect those rare cases in which low demand coupled with large supply from renewable

The model embeds also a commonly adopted policy mechanisms designed to accelerate investments in renewable technologies, namely the feed-in tariff scheme.[4] In our setting, the tariff is meant to finance the investment cost per kilowatt-hour which, for some renewable technologies, is deemed so large so as to determine a null or insufficient rate of adoption compared to the established target.

The model's objective is to identify the drivers of "renewable" generators capacity and production choices. The analysis of the equilibrium reveals that the "renewable" generator exploits the merit order rule which governs spot electricity markets to invest and produce as if it were a sort of Stackelberg leader. While producer's preferences over strategies seem not to be influenced by the average value of capacity availability, consumer surplus differs substantially according to it. Given that production of electricity from the renewable source depends on actual weather conditions, the analysis of ex-post payoffs reveals that "renewable" producer's preferences over strategies may be reversed even for small errors in the forecasting of the true value of the average capacity availability factor when the investment cost in the renewable technology is relatively low. In this case, the incentives for strategic behavior may be even stronger. The main insights of the model are barely sensitive to changes in the relative market power of competitors: even when the "renewable" generator behaves as a competitive fringe in the spot market, it is able to influence equilibrium outcome to its own advantage through investment choices although to a smaller degree than in the standard setting.

The paper is organized as follows. Section 2 reviews the relevant literature. Sections 3 and 4 are dedicated the model and its resolution. Section 5 presents the ex-post analysis of strategies. Section 6 discusses model's results and their sensitivity to the relaxation of the assumptions on market power and dimension of the renewable producer. All relevant calculations of the baseline model are reported in Appendix A while the detailed analysis of the extension in which the renewable producer behaves as a competitive fringe is included in Appendix B.

2   Literature review

A strand of literature on competition in liberalized power markets focuses on firms' short run behaviours (bid strategies in the spot market) while a second strand is concerned with the analysis of long run performances (impact of competition on capacity investments). Often the models in the latter group constitute an extension of those in the former; when this is not the case, it is always possible to envisage such a development: whatever is the selected setting for the second stage competition, this stage is or may be preceded by a first one in which firms make investment decisions. This section summarizes the theoretical models proposed in the literature, provides an overview of their main results and examine the attractiveness of their application in the study of competition between "traditional" and "renewable" generators.[5]

A first approach consists in applying Kreps and Scheinkman (1983) two stage model in which a Bertrand-Edgeworth price competition is preceded by a quantity decision or "capacity choice", yielding the standard Cournot equilibrium outcome.

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power plants depresses the spot price to zero.

[4]In general the feed-in tariff rewards the kilowatt-hours produced with renewable technologies by offering to the producers a fixed purchasing price which is generally higher than the market price. For a general discussion on support schemes for renewable technologies see Couture and Gagnon (2010).

[5]We do not consider those papers in which the spot market is perfectly competitive (or regulated) and the price is fixed to the marginal cost of the last unit called into operation, such as in Meunier (2010).

Extensions and refinements of the basic model include the works of Deneckere and Kovenock (1996), Reynolds and Wilson (2000) and Fabra and de Frutos (2011). According to von der Fehr and Harbord (1998) the major limit of this approach relates to the fact that firms are paid on the basis of each own bid, rather than on the one of the last unit called into operation, as happens in real power markets. On the other hand, this model provides a formal justification for the elimination of marginal cost bidding strategy in a Bertrand setting when capacity is constrained.[6]

A second approach is based on the Supply function model of Klemperer and Meyer (1989) which has been extended to power markets by Green and Newbery (1992). In this setting firms compete in supply functions, i.e. by setting combinations of price-quantity pairs, given the uncertainty of demand. Although the model closely represents the reality of spot electricity markets where firms' bids combinations of price and quantity (though supply functions are not really continuous), its predictive value is very poor because possible equilibria, when defined, range between the Cournot and the Bertrand solutions. Given the uncertainty of second stage equilibria, the attractiveness of adding a first stage with investments is very low.

The third approach consists in modelling competition in the second stage as a sealed bid, multi-unit auction in which payments to the two competitors are equal to the highest accepted bid in the uniform auction format and to own bid in the discriminatory auction format. The auction is preceded by an investment stage in which firms choose their capacity prior to bid in the market. The auction approach, developed by Fabra et al. (2011) extending the works of von der Fehr and Harbord (1993), von der Fehr and Harbord (1997), Fabra et al. (2006), has been largely appreciated for closely reproducing real market designs and the nature of competition in spot markets. On the other hand the model results difficult to manipulate, for instance by adding technological asymmetries, due to problems of non-uniqueness and non-existence of sub-game perfect pure-strategy equilibria for some values of the demand. Concerning the results, in both types of auction bidding at marginal cost is a Nash equilibrium only when the demand is lower than the capacity of the smaller firm, whereas bidding at price cap is a Nash equilibrium when the demand is larger than the sum of the two capacities. The aggregate capacity in both auction formats results to be smaller compared to the first best's capacity and its distribution is asymmetric although firms are full symmetric ex-ante.

The last but most appealing approach for our research purpose assumes that power generators compete in quantities. Tishler et al. (2008) study the equilibrium in an oligopolistic two stage game in which firms invest in capacity in the first stage knowing the probability distribution of future demand and select their production in the second stage once the demand reveals.[7] While the first stage is played once, the second stage is repeated a number of independent times over the considered temporal horizon. In the first extension of this model (Milstein and Tishler, 2012) a base-load and a peak-load technologies characterized by a trade-off between capacity and operation costs are available. In a second extension (Milstein and Tishler, 2011) firms may invest in a combined cycle gas turbine (CCGT) plant or in a photovoltaic (PV) plant whose profitability depends on the probability of daily sunshine. In the first extension the authors show that the equilibria differs when firms are allowed or not to invest in both technologies. In particular, when firms can employ both technologies aggregate industry capacity results to be smaller, the share of base-load technology larger and total welfare bigger. In the second extension, the authors demonstrate that the uncertainty of weather conditions reduces the profitability of

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[6]This result is similar to auction model's prediction.
[7]For a theoretical analysis of such games see Gabszewicz and Poddar (1997).

PV plants and its attractiveness: only when the PV to CCGT capacity cost ratio declines sharply, the adoption of PV becomes positive although it remains limited. The latter setting presents however some limitations: the optimization problem has no closed form solution and must be solved by numerical methods; moreover, the result on the scarce adoption of renewable technology at equilibrium is partly biased by the fact that the authors discard the merit order rule in dispatching.[8]

In the same vein, Murphy and Smeers (2005) study capacity investments when a base load and a peak-load providers compete in an open-loop Cournot setting in which investments and production take simultaneously place and in a closed-loop Cournot model in which investment decisions are taken in the first stage of the game and production levels are chosen in the second stage. The authors show that the total capacity at equilibrium in the closed-loop setting is equal or larger than the capacity chosen in the open loop setting: this happens because in the closed loop model the base load producer has an incentive to invest more in the first stage and to produce more in the second stage compared to open loop setting, thus distorting in its favour short run market outcomes.[9] Interestingly, both Murphy and Smeers (2005) and Milstein and Tishler (2012) highlight that base-load investments result to be "strategic" in the sense that they allow to modify short run competition. In the next paragraphs we present our model of competition between "renewable" and "traditional" power producers in which the assumptions of quantity competition and sequential investment-production decisions are maintained although they may have different interpretations. Moreover, our setting differs from Milstein and Tishler (2011) because it takes explicitly into account the relevance of the merit order rule in determining equilibrium investment and production choices.

3 The model

In real spot markets, electricity suppliers submit simultaneously and independently bid prices at which they are willing to supply their available capacity. The market operator ranks the bids by merit order defining a supply schedule monotonically increasing in function of price offers. The firms that are called into operation are all paid the system marginal price which corresponds to highest accepted bid. We examine competition between "traditional" and "renewable" power producers using a modified version of the *Dixit model* for entry deterrence (Dixit, 1980). This choice stems from the following reasons.

First of all, because of the merit order rule the power from renewable sources is always the first to be brought on line in spot electricity markets. This favourable ranking may be interpreted as a sort of first mover advantage. As in a standard entry deterrence game the profitability of entry depends on the capacity choices made by the incumbent in previous stages, in power sector the profitability of investments in "traditional" technologies rests on the size of the residual demand, which in turn is determined by the capacity installed by "renewable" producer. In our model the "renewable" power plant is thus the incumbent and the "traditional" producer is the entrant who behaves as a follower in the Stackelberg game for capacity investment.

Secondly, the *Dixit model* is sufficiently flexible to allow for several types of competition in the post entry game: firms may play in a perfect competitive setting

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[8]If on the one hand CCGT investments result to be more profitable than PV investments because CCGT production does not depend on weather conditions, on the other hand CCGT plants have less probability to be dispatched and hence to produce.

[9]This "strategic" effect refers to a decrease in rival's production (peak-load provider) due an increase in the market share of firm with smaller marginal costs (base-load provider).

(Spence, 1977); in a Cournot setting (Dixit, 1980; Spulber, 1981; Ware, 1984; Bulow et al., 1985; Maskin, 1997); in a Stackelberg setting with the entrant as leader (Dixit, 1980) or follower (Spulber, 1981; Saloner, 1985; Basu and Singh, 1990); in a Bertrand setting (Allen et al., 2000). Moreover in each setting a certain degree of uncertainty about demand and/or cost functions may be introduced (Maskin, 1997). In real power markets firms are supposed to compete in prices. However, in a stylized model with a "renewable" and a "traditional" power producers firms rather play a quantity game since the "renewable" power plant can always bid at zero due to its cost advantage and the "traditional" producer is constantly marginal. We design the post-entry game as a Cournot competition in the baseline model and as quantity competition between a dominant firm and a competitive fringe in the extended model, accounting for the fact that "renewable" producers are price takers in spot markets. Quantity competition presents the additional advantage that both firms receive the same price as in a uniform price auction. Finally, this framework easily allows to introduce uncertainty on the supply side due to the intermittency of production from the renewable power plant.

We propose two alternative structures for the strategic game. In the baseline model (two stage game), firms compete in a two stage game with the following timing:

- in the first stage the "renewable" firm chooses its capacity investment which is irreversible in the sense that capacity already installed cannot be dismissed;

- in the second stage of the game firms compete in quantities: the "traditional" firm selects simultaneously its capacity investment and its production level[10] while the "renewable" firm may increase its capacity prior to compete for production.

In the extended model (three stage game), the "renewable" firm is assumed to behave like a price taker fringe in the spot market. Hence the post-entry game is a Stackelberg game with the entrant (the "traditional" firm) playing the role of leader. The timing of the game is the following:

- in the first stage the "renewable" firm chooses its capacity investment which is irreversible in the sense that capacity already installed cannot be dismissed;

- having observed the capacity chosen by its rival, in the second stage the "traditional" firm selects its capacity and its production;

- in the third stage, the "renewable" firm chooses its production level.

We analyze all the results of the two stage game in the next sections while the outcome of the three stage game is discussed in the conclusions. The two stage and three stage games may be interpreted as reproducing two alternative market designs for "renewable" generators participation in the spot market: on the one hand the production from several renewable power plants may be aggregated by a unique entity bidding on behalf of producers;[11] on the other hand, the supply of "renewable" power may be more fragmented and each generator may participate individually in the spot market. As we will see, the qualitatively results of the model hold in both alternative market structures.

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[10]For the "traditional" firm capacity and production levels will always be identical given that they are selected simultaneously. Therefore, if in reality capacity investments are already sunk which is very often the case for CCGT power plant, this stage of the game may be interpreted as the one in which the "traditional" firm only adjusts its production.

[11]See for instance the case of Gestore Servizi Energetici in Italy, www.gse.it.

4 Two stage game

In the baseline model it is assumed that two firms compete in the power market: the first firm, S, manages a photovoltaic power plant (henceforth PV) and the second firm, G, operates a combined cycle gas turbine plant (henceforth CCGT). Production is denoted by q_i, $i = s, g$, and generation capacities by k_i, $i = s, g$. The investment cost per unit of capacity is $I_i > 0$, $i = s, g$. Production gives rise to a variable cost c_i, $i = s, g$, for production levels below capacity while production above capacity is infinitely costly. We assume without loss of generality that $0 = c_s < c_g = c$ and that $c + I_g < I_s$, i.e. firm G has lower average costs.[12] It is further assumed that the availability of photovoltaic capacity for production depends on weather conditions. Therefore for each level of installed capacity k_s the available capacity is $x k_s$, where x is the realization of a random variable $X \in [0, 1]$. Firms know the continuous distribution function of the random variable X as well as its expected value, $\mathbb{E}[x] = x^*$. Firms face a linear inverse demand function, $p(Q) = a - bQ$, where $Q = q_s + q_g \subseteq (0, x k_s + k_g)$. An amount τ is awarded to the producer for each unit of PV capacity built. The tariff aims at reducing the true investment cost in the renewable technology, I_{pv}, which is deemed so high so as to make entry unprofitable ($I_{pv} > a$). Therefore the tariff verifies the following inequality, $I_{pv} - \tau = I_s < a$.[13]

The structure of the game is the following. In the first stage S chooses its capacity, k_s: the investment is irreversible in the sense that capacity already installed cannot be dismissed. In the second stage of the game firms compete in quantities: G selects simultaneously its capacity, k_g, and its production level, q_g, while S may increase its capacity prior to compete for production. Note that the quantities of electricity produced by G and S are strategic substitute, which means that marginal revenue of each firm is decreasing in rival's output. This assumption is equivalent to assume that both firms' reaction functions are always downward sloping and it is a sufficient condition to ensure that the established firm will never install excess capacity, i.e. it will never install in the first stage of the game a capacity which will be left idle in the final stage (Bulow et al., 1985).

4.1 Second stage solutions

The game is solved by backward induction to find the sub-game perfect Nash equilibrium. In the last stage of the game G selects production and capacity which maximize its expected profit:[14]

$$\underset{q_g, k_g}{\text{Max}} \quad \mathbb{E}[\Pi_g] = \mathbb{E}[p(q_s, q_g)q_g - cq_g - I_g k_g] \quad \text{subject to}$$
$$q_g \leq k_g \tag{1}$$

At the optimum the capacity constraint is binding since G would never invest in a capacity it cannot use for production. Therefore in each equilibrium we will indicate only the quantity produced by G, knowing that the capacity is sized accordingly. The

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[12]The concept of average cost may be associated to that of "Levelised Cost of Energy (LEC)" which is a commonly used instrument to compare costs for unit of electricity generated from different sources. The LEC is an economic assessment of unit generation costs over the whole lifetime of a power plant which includes initial investment, operations and maintenance costs, costs of fuel and capital. According to IEA 2012 Annual Energy Outlook, the dollar cost per megawatt-hour of a conventional combined cycle plant entering in service in 2017 is 68,6 dollars while for a solar photovoltaic plant is 156,9 dollars (IEA, 2012).

[13]The role of feed-in tariff here is only to make profitable the adoption of PV technology.

[14]The randomness in G's profits depends on price's uncertainty which is turn is caused by the uncertainty in S's production level.

reaction function of G is:

$$R_g(q_s) = q_g = \frac{a - bq_s - c - I_g}{2b} \tag{2}$$

The reaction function of S is a kinked curve, whose equation is the solution to the following profit maximization problem:

$$\underset{q_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}[p(q_s, q_g)q_s - C(q_s, k_s)] \quad \text{where} \tag{3a}$$

$$C(q_s, k_s) = \begin{cases} 0 & \text{if } q_s \leq x^* k_s \\ \left(\frac{I_s}{x}\right) q_s & otherwise \end{cases} \tag{3b}$$

The shape of the reaction curve depends on the capacity choices made by firm S in the previous stage. When in the last stage of the game S selects a production level below or equal to the available installed capacity, $x^* k_s$, it does not incur in any costs given that capacity investment has been already paid and production with renewable technologies is costless. In this case $C(q_s, k_s) = 0$. Contrariwise, if the capacity installed in the previous stage is not sufficient to meet S's optimal production level in the last stage, a new investment may be undertaken bearing the associated cost. S's relevant cost function in this case is $C(q_s, k_s) = \left(\frac{I_s}{x}\right) q_s$. Note that S's expected marginal revenues are decreasing in the quantity of electricity provided by firm G:

$$\mathbb{E}[MR_s] = a - 2bq_s - bq_g \tag{4}$$

For large quantities of q_g, S's expected marginal revenue curves cross expected marginal cost at zero (MR_1). Similarly for small quantities of q_g, S's expected marginal revenue curves cross expected marginal cost at $\frac{I_s}{x^*}$ (MR_3). In the intermediate case expected marginal revenue curves cross expected marginal cost curve at the kink (MR_2).
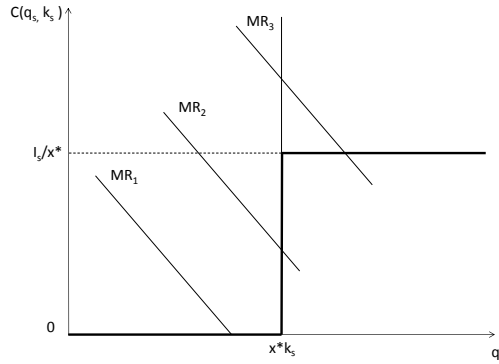
Figure 1: Expected marginal revenue and marginal cost curves

It is therefore possible to calculate the thresholds of q_g that make firm S to switch from a cost curve to another, thus changing the relevant reaction function. Let us define:

- $q_g^h = \frac{a - 2bx^* k_s}{b}$ as the quantity of q_g such that, $\forall q_g > q_g^h$:

$$\mathbb{E}[MR_s(q_s, q_g)] = 0 \tag{5a}$$

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g}{2b} \qquad (5b)$$

- $q_g^l = \frac{x^*(a - 2bx^*k_s) - I_s}{bx^*}$ as the quantity of q_g such that, $\forall q_g < q_g^l$:

$$\mathbb{E}[MR_s(q_s, q_g)] = \frac{I_s}{x^*} \qquad (6a)$$

$$R_s(q_g) = q_s = \frac{x^*a - bx^*q_g - I_s}{2bx^*} \qquad (6b)$$

- $\forall q_g$ such that $q_g^l < q_g < q_g^h$, firm S produces at (available) capacity:

$$\bar{R}_s = q_s = x^*k_s \qquad (7)$$

Firm S reaction function is the bold line depicted in Figure 2. Note that when relevant marginal costs include investment cost, the reaction function moves inward. According to the capacity installed in the first period, we may observe three different Nash equilibria in the last stage of the game (Case A, Case B and Case C). We firstly calculate each equilibrium in last stage and then we solve backward to find first stage's solutions. Finally we compare the payoffs to estimate S's optimal strategy.
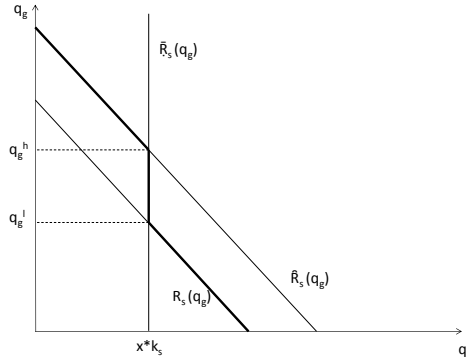
Figure 2: Firm S reaction function

Strategy A: small photovoltaic capacity

If firm S has installed a very small level of capacity in the first stage, it would probably like to increase it in the last stage. In this case, Nash equilibrium occurs where the reaction function of firm G crosses the reaction function of firm S in a point on $R_s(q_g)$. The solution of the last stage game is the usual Cournot-Nash equilibrium. Firm S chooses its optimal quantity as the solution to the following profit maximization problem:

$$\underset{q_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}\left[p(q_s, q_g)q_s - \left(\frac{I_s}{x} \right) q_s \right] \qquad (8)$$

The optimal response is:

$$R_s(q_g) = q_s = \frac{x^*a - bx^*q_g - I_s}{2bx^*} \tag{9}$$

Combining S and G reaction functions, we obtain equilibrium quantities, price and profits:

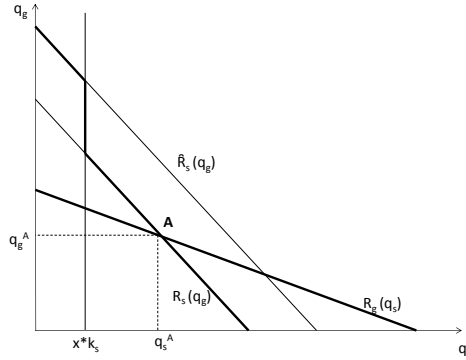$$q_s^A = \frac{x^*(a + c + I_g) - 2I_s}{3bx^*} \tag{10a}$$

$$q_g^A = \frac{x^*[a - 2(c + I_g)] + I_s}{3bx^*} \tag{10b}$$

$$p^A = \frac{x^*(a + c + I_g) + I_s}{3x^*} \tag{10c}$$

$$\Pi_s^A = \frac{[x^*(a + c + I_g) - 2I_s]^2}{9bx^{*2}} \tag{10d}$$

$$\Pi_g^A = \frac{\{x^*[a - 2(c + I_g)] + I_s\}^2}{9bx^{*2}} \tag{10e}$$

The equilibrium is represented in Figure 3. The standard Cournot Nash equilib-

Figure 3: Equilibrium in case A

rium arises in the second stage of the game if in the earlier stage firm S has installed:

$$k_s^A \leqslant \frac{q_s^A}{x^*} = \frac{x^*(a + c + I_g) - 2I_s}{3bx^{*2}} \tag{11}$$

Strategy B: large photovoltaic capacity

If firm S has installed a large capacity in the first stage, it presents a cost advantage relative to G in the last stage competition. In this case, the reaction function of firm S moves outward toward $\tilde{R}_s(q_g)$. Firm S determines its optimal quantity as the solution to the following maximization problem:

$$\underset{q_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}[p(q_s, q_g)q_s] \tag{12}$$

yielding the reaction function:

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g}{2b} \tag{13}$$

Again, combining S and G reaction functions gives the optimal quantities, price and profits:

$$q_s^B = \frac{a + c + I_g}{3b} \tag{14a}$$
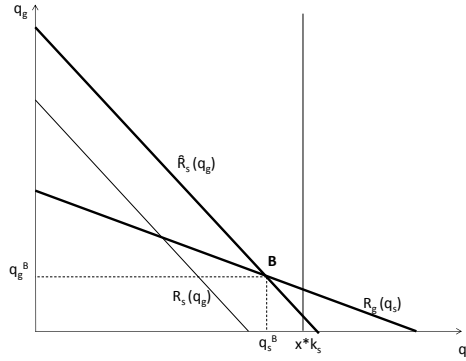
$$q_g^B = \frac{a - 2(c + I_g)}{3b} \tag{14b}$$

$$p^B = \frac{a + c + I_g}{3} \tag{14c}$$

$$\Pi_s^B = \frac{(a + c + I_g)^2}{9b} \tag{14d}$$

$$\Pi_g^B = \frac{[a - 2(c + I_g)]^2}{9b} \tag{14e}$$

This equilibrium is represented in Figure 4 and arises if firm S has installed in the earlier stage of the game:

$$k_s^B \geqslant \frac{q_s^B}{x^*} = \frac{a + c + I_g}{3bx^*} \tag{15}$$

Figure 4: Equilibrium in case B

Note that $\Pi_g^B > 0$ if $a > 2(c + I_g)$. If $\Pi_g^B < 0$ firm G prefers not to produce, so we should exclude this opportunity.

Strategy C: intermediate photovoltaic capacity

When S's capacity size is between the thresholds determining equilibria A and B, firm S produces at available capacity, $q_s = x^* k_s$, and firm G behaves as a Stackelberg follower reacting to the quantity produced by its rival. Therefore, G's reaction function described in eqs. (2) may be rewritten as:

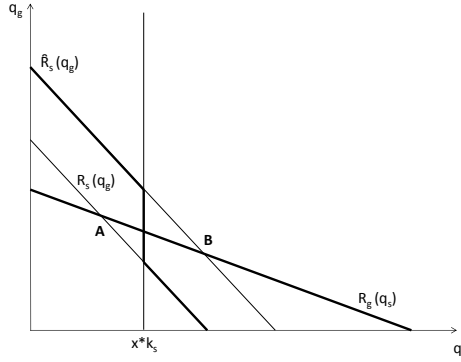$$R_g(k_s) = q_g^C = \frac{a - bx^*k_s - c - I_g}{2b} \tag{16}$$

Equilibrium price and profits in implicit form are:

$$p^C = \frac{a - bx^*k_s + c + I_g}{2} \tag{17a}$$

$$\Pi_s^C = \left(\frac{a - bx^*k_s + c + I_g}{2} \right) x^*k_s \tag{17b}$$

$$\Pi_g^C = \frac{(a - bx^*k_s - c - I_g)^2}{4b} \tag{17c}$$

The equilibrium in case C is represented in Figure 5.

Figure 5: Equilibrium in case C

4.2 First stage solutions

In order to calculate the explicit pay-off in Case C, the first stage of the game must be solved. In the first stage firm S chooses k_s so as to maximize its expected profits in case C:

$$\underset{k_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}[p(xk_s, q_g)xk_s - I_sk_s] \tag{18}$$

Using the reaction function of G and calculating the FOC of the problem, we get equilibrium quantities, price and profits:

$$q_s^C = \frac{x^*(a + c + I_g) - 2I_s}{2bx^*} \tag{19a}$$

$$q_g^C = \frac{x^*[a - 3(c + I_g)] + 2I_s}{4bx^*} \tag{19b}$$

$$p^C = \frac{x^*(a + c + I_g) + 2I_s}{4x^*} \tag{19c}$$

$$\Pi_s^C = \frac{[x^*(a + c + I_g) - 2I_s]^2}{8bx^{*2}} \tag{19d}$$

$$\Pi_g^C = \frac{\{x^*[a - 3(c + I_g)] + 2I_s\}^2}{16bx^{*2}} \tag{19e}$$

This solution arises if S instals in the first stage of the game the following capacity:

$$k_s^C = \frac{x^*(a + c + I_g) - 2I_s}{2bx^{*2}} \tag{20}$$

4.3 Optimal strategy selection

Firm S selects its optimal strategy by comparing net profits in each of the three cases regardless if the investment has been paid in the first or the second stage of the game. We indicate net profits with a * to distinguish them from gross profits:[15]

$$\Pi_s^{A^*} = \frac{[x^*(a + c + I_g) - 2I_s]^2}{9bx^{*2}} \tag{21a}$$

$$\Pi_s^{B^*} = \frac{(a + c + I_g)((a + c + I_g)x^* - 3I_s)}{9bx^*} \tag{21b}$$

$$\Pi_s^{C^*} = \frac{[x^*(a + c + I_g) - 2I_s]^2}{8bx^{*2}} \tag{21c}$$

We remark that firm S prefers to invests more in the first stage of the game rather than to postpone investments to the second stage. Indeed strategy A is always dominated by strategy C given that the following inequalities is verified for any value of x^*:

$$\Pi_s^{C^*} = \frac{[x^*(a + c + I_g) - 2I_s]^2}{8bx^{*2}} > \frac{[x^*(a + c + I_g) - 2I_s]^2}{9bx^{*2}} = \Pi_s^{A^*} \tag{22}$$

On the other hand, strategy C is preferred to strategy B only when the following inequality holds:

$$\Pi_s^{C^*} = \frac{[x^*(a + c + I_g) - 2I_s]^2}{8bx^{*2}} > \frac{(a + c + I_g)((a + c + I_g)x^* - 3I_s)}{9bx^*} = \Pi_s^{B^*} \tag{23}$$

Since both b and x^* are positive the previous condition reduces to:

$$[(a + c + I_g)x^* - 6I_s]^2 > 0 \tag{24}$$

Strategy C is then preferred to B when:

$$\textbf{Case 1:} \quad a + c + I_g < 6I_s \quad \Rightarrow \forall \, x^* \tag{25}$$

$$\textbf{Case 2:} \quad a + c + I_g \geq 6I_s \quad \Rightarrow x^* \neq \frac{6I_s}{a + c + I_g} \tag{26}$$

When parameters' values are those of Case 1, strategy C is preferred to strategy B for any value of x^*. This means that, regardless of the average value of capacity availability, the photovoltaic generator will exploit the merit order rule to invest and produce as if it were a Stackelberg leader. Notwithstanding, instead of building as much capacity as it would be needed to compete with zero variable costs, the "renewable" producer will prefer to be strategic, restrain the output and leave a larger market share to its competitor because this will result in higher profits. This result is formalized in Proposition 1.

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[15]Note that $\Pi_s^A = \Pi_s^{A^*}$ and $\Pi_s^C = \Pi_s^{C^*}$

Proposition 1. *Because of merit order rule, the "renewable" producer has a strategic incentive to increase its optimal capacity and production behaving like a Stackelberg leader. However, it will not exploit its "first mover advantage" to its maximum because this may cause the profits to decrease.*

Only when parameters' values are those of Case 2 and the following equality holds:

$$p^B = \frac{2I_s}{x^*} \tag{27}$$

the two strategies have exactly the same pay-off and S is indifferent between them, which is clearly a very restrictive case.

Lemma 1. *For most of the parameters' values the average availability of installed capacity does not change the "renewable" producer's preferences between strategies.*

From consumers' point of view, however, strategies B and C differ substantially depending of the value of x^*. Given the monotonicity of demand function it suffices to calculate which equilibrium guarantees the lowest price to assess when consumers' are better off. Equilibrium C leads to a higher consumers' surplus with respect to equilibrium B if and only if:

$$x^* > \frac{6I_s}{a + c + I_g} \tag{28}$$

This result seems to indicate that there is some room for welfare improving public interventions. Indeed, if on the one hand the average availability of photovoltaic capacity depends on technology and cannot be modified, on the other hand the value of the right hand side of equation (28) is increasing in the investment cost of renewable technology: a policy which reduces such cost increases consumer surplus. We may represent with the help of a graph the preferences over strategies of firm S and consumers for different values of x^* (Figure 6). It is worthy to note that if parameters values are those of Case 1 consumers are never better off with strategy C because the right hand side of equation (28) is larger than 1 which is not possible.
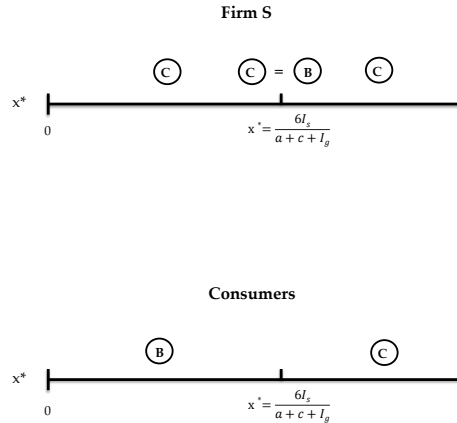
Figure 6: Preferences over strategies

The solution of Case 1 above arises when the investment cost of photovoltaic capacity is relatively large. When parameters respect the condition for such equilibrium

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there is always a conflict between consumers and firm S interest: the former will always prefer equilibrium B, while the latter will always play the strategy leading to equilibrium C. In this case consumers' loss is inversely related to the value of average capacity availability, i.e. the larger is x^* the smaller is the difference between consumer surplus in equilibria C and B. Conversely, when investing in renewable capacity is relatively cheap, there is room for consumers and firm S interests to converge: both may be better off in equilibrium C if the value of average capacity availability is larger than a certain threshold. These results are formalized in Proposition 2 and Lemma 2.

Proposition 2. *Merit order rule may lead to an equilibrium which benefits both the "renewable" producer and the consumers.*

Lemma 2. *A public intervention which reduces investment cost in the "renewable" technology increases the likelihood of a market outcome in which both the "renewable" producer and the consumers are better-off.*

5 Analysis of ex post profits

Investment choices are taken on the basis of the average value of capacity availability, x^*, while production firm S may be adjusted according to the realized value of x. G can modify its production as well but it is constrained by the size of its installed capacity. It may be interesting to calculate the *ex post* expected profits of firm S, i.e. the profits it gains once it has invested in capacities k_s^C or k_s^B and it produces according to the real value of x. In both cases the pay-off is:

$$\Pi_s = (a - bq_g - bxk_s)xk_s - I_s k_s \tag{29}$$

We may substitute in eq. (29) the optimal values of k_s^C and k_s^B calculated as functions of x^* and the optimal quantity of firm G.[16] We recall that G produces the lower quantity between its installed capacity and its optimal production given the electricity supplied by S:

$$q_g^{B,C} = \frac{a - b \max(x, x^*) k_s^{B,C} - c - I_g}{2b} \tag{30}$$

Calling $A = a + c + I_g$, ex post profits are:

$$\Pi_s^B[x] = -\frac{A}{3bx^*}\left(I_s + \frac{2Ax^2 - 3Axx^* - Ax \max(x, x^*)}{6x^*}\right) \tag{31a}$$

$$\Pi_s^C[x] = (Ax^* - 2I_s)\frac{2(x - x^*)(Axx^* - 2I_s(x + x^*)) + x(2I_s - Ax^*)\max(x, x^*)}{8bx^{*4}} \tag{31b}$$

To calculate their expected value, we firstly use a generic probability density function, $P(x)$, defined for $x \in [0, 1]$. For a generic function the following condition must hold:

$$\mathbb{E}[f] = \int_0^1 f(x)P(x)dx \tag{32}$$

Expected profits are then:[17]

$$\mathbb{E}[\Pi_s^{B,C}] = \int_0^1 \Pi_{B,C}(x)P(x)dx \tag{33a}$$

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[16]All calculations are reported in Appendix A.

[17]Note that we have dropped the subscript s for expositional convenience.

$$\mathbb{E}[\Pi_s^B] = -\frac{AI_s}{3bx^*} - \frac{A^2 E[x^2]}{9bx^{*2}} + \frac{A^2}{6b} + \frac{A^2 M}{18bx^{*2}} \tag{33b}$$

$$\mathbb{E}[\Pi_s^C] = \frac{I_s B}{2bx^{*2}} - \frac{AB}{4bx^*} - \frac{B^2}{4bx^{*4}} E[x^2] + \frac{MB^2}{8bx^{*4}} \tag{33c}$$

where:

$$M = \int_0^1 x \max(x, x^*) P(x) dx \tag{34a}$$

$$A = a + c + I_g \tag{34b}$$

$$B = 2I_s - Ax^* \tag{34c}$$

Recalling that $\mathbb{E}[x] = x^*$, we may rewrite the expected profits of strategies B and C using the definition of variance of a random variable, $\mathrm{Var}[x] = \mathbb{E}[x^2] - \mathbb{E}[x]^2$. After some manipulations we get:

$$E[\Pi_B] = \frac{A^2}{18b} - \frac{AI_s}{3bx^*} + \frac{A^2}{18bx^{*2}} (M - 2\mathrm{Var}[x]) \tag{35a}$$

$$E[\Pi_C] = \frac{2I_s B - B^2}{4bx^{*2}} - \frac{AB}{4bx^*} + \frac{B^2}{8bx^{*4}} (M - 2\mathrm{Var}[x]) \tag{35b}$$

For strategy C to be ex post superior to strategy B the condition $E[\Pi_B] < E[\Pi_C]$ must hold. This condition is equivalent to:

$$\frac{A^2}{18} - \frac{AI_s}{3x^*} + \frac{A^2}{18x^{*2}} (M - 2\mathrm{Var}[x]) < \frac{B^2}{8x^{*4}} (M - 2\mathrm{Var}[x]) \tag{36}$$

After some manipulations the inequality can be reduced to:

$$\hat{x}^2 s(s-1) < \frac{1 - 6s + 5s^2}{4s^2} (M - 2\mathrm{Var}[x]) \tag{37}$$

where

$$I = 6I_s \tag{38a}$$

$$\hat{x} = \frac{I}{A} \tag{38b}$$

$$s = \frac{x^*}{\hat{x}} \tag{38c}$$

To get some insights on the effect that the variance of x may have on the *ex post* payoff of strategies we have to specify a distribution function. We performed some simulations using a uniform distribution function defined as:

$$P(x) = \begin{cases} \frac{1}{2\epsilon} & \text{for } x^* - \epsilon \leq x \leq x^* + \epsilon \\ 0 & \text{otherwise} \end{cases} \tag{39}$$

With this distribution function we have:

$$M = \frac{\epsilon^2}{6} + \frac{x\epsilon}{4} + x^2 \tag{40a}$$

$$\mathrm{Var}[x] = \frac{\epsilon^2}{3} \tag{40b}$$

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We can finally simplify inequality (37) so as to obtain:

$$\hat{x}^2 s < \frac{1}{16s^2}(5s-1)(4\hat{x}^2 s^2 + \hat{x}s\epsilon - 2\epsilon^2) \tag{41}$$

We perform some simulations for different values of $\hat{x}$. The results are reported in Figures 7 to 14. Note that the right-hand sided figures show simulation's results when the parameters I_s, a, c_g and I_g have values corresponding to Case 1 in the ex-ante analysis, i.e. relatively large investment cost in renewable technologies, while left-hand sided figures display simulation's results for parameters' values corresponding to Case 2, i.e. relatively small investment cost in renewable technologies. We recall that in the ex ante analysis indifference between strategies B and C is possible only in Case 2 and only for a specific value of x^*. In our simulation, red areas represent the values of parameters for which strategy C is still ex-post preferred, whereas purple areas the values for which strategy B becomes more profitable. We consider that the forecasting of the true value of the average capacity availability is subject to limited errors, i.e. $\epsilon = 0, 1$.

We remark that when investment cost in renewable technology is quite large, strategy B is never preferred either ex-ante or ex-post (Figures 8, 10, 12, 14). Conversely, when investment cost is relatively low the ex post analysis suggests that strategy B yields greater profits even for smaller values of x^* than those estimated in the ex-ante analysis, thereby increasing the range of parameters' values for which strategy B is preferred by the PV generator (Figures 9, 11, 13). For instance, when $\hat{x} = 0.75$ (see Figure 14) strategy B is ex-ante preferred if and only if $x^* = 0.75$ while the ex-post analysis reduces the range to $0.675 < x^* < 0,75$. We formalize these result in Lemma 3 and Proposition 3.

Lemma 3. *When investment cost is relatively low, "renewable" producer preferences between strategies may be reversed even for small errors in the forecasting of the true value of capacity availability factor.*

Proposition 3. *According to the ex-post analysis of pay-off the strategic effect of spot market design on investment and production choices of "renewable" producer may be stronger than what suggested by the ex-ante analysis alone.*

6   Conclusions and extensions

We proposed a stylized model for the analysis of investment and production incentives in decentralized electricity markets when a traditional power generator faces competition from a producer employing an intermittent technology. Although competition in generation seems to be substantially animated by new entrants investing in renewable technologies, the study of interactions between "traditional" and "renewable" power producers still remains an almost unexplored field of research. Our model is a modified version of the *Dixit model* for entry deterrence with Cournot competition in the post entry stage. This choice stems from two reasons. Firstly, because of merit order rule the power from renewable sources is always the first to be brought on line in spot electricity markets. This favorable ranking may be interpreted as a sort of first mover advantage similar to that one of the incumbent in the Dixit model. Indeed, in power sector the profitability of investments in "traditional" technologies rests on the size of the residual demand, which in turn is determined by the capacity installed by "renewable" producer. Therefore the "renewable" producer is a sort of incumbent and the "traditional" producer is the entrant who behaves as a follower
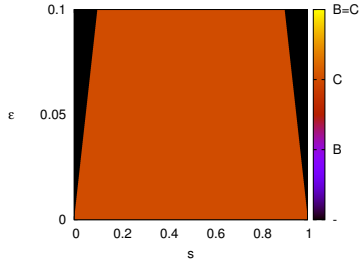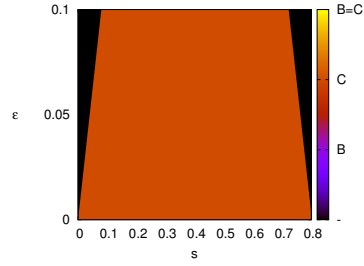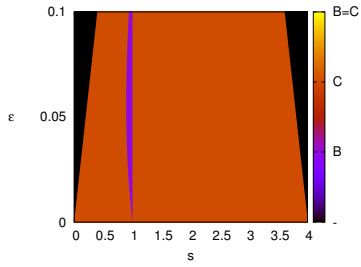
Figure 7: $\hat{x} = 1$

Figure 8: $\hat{x} = 1.25$

Figure 9: $\hat{x} = 0.25$

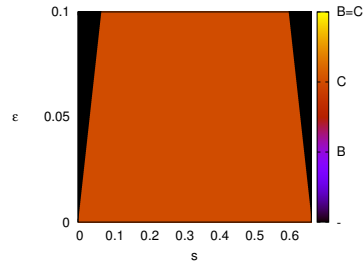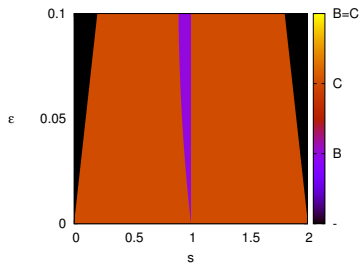**Figure 10:** $\hat{x} = 1.5$
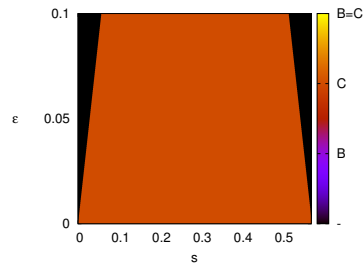

Figure 11: $\hat{x} = 0.5$

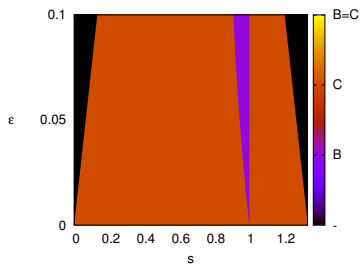**Figure 12:** $\hat{x} = 1.75$

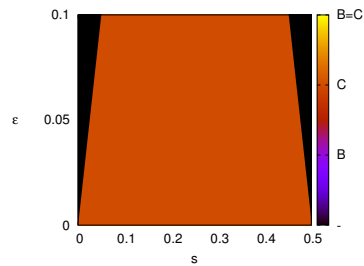
Figure 13: $\hat{x} = 0.75$

Figure 14: $\hat{x} = 2$

in the Stackelberg game for capacity investment. Secondly, the *Dixit model* is sufficiently flexible to allow for several types of competition in the post entry game and in each setting a certain degree of uncertainty about demand and/or cost functions may be introduced. We have modeled post-entry stage as a Cournot competition and the uncertainty depends on the availability of PV capacity. In real power markets firms are supposed to compete in prices. However, in a stylized model with a "renewable" and a "traditional" power producers firms rather play a quantity game since the "renewable" power plant can always bid at zero and the "traditional" producer

is constantly marginal. Quantity competition presents the additional advantage that both firms receive the same price as in a uniform price auction used in real markets.

Our analysis suggests that the "renewable" generator exploits merit order rule to invest and produce as if it were a Stackelberg leader. While including considerations about the average availability of installed capacity does not change preferences over strategies of "renewable" generator for most of the parameters' values, consumer surplus differs substantially according to it. This result seems to indicate that there is some room for welfare improving public interventions: indeed, if on the one hand the average availability of renewable capacity depend on technology and cannot be modified, on the other hand consumer surplus can be increased (regardless to the strategy chosen by the firm) by decreasing investment cost in renewable technology. Interestingly, the ex-post analysis of pay-off reveals that profits ranking, and hence preferences over strategies, may be reversed even for small errors in the forecasting of the average capacity availability factor and so the incentives for strategic behavior may be stronger. This result suggests that the only ex-ante analysis of the game may be misleading and must be always coupled with an ex-post analysis.

An extension of our model consists in relaxing the assumptions on market power and dimension of the PV producer. The whole analysis with all relevant calculations is reported in the Appendix B. In the extended model, we adopt the "dominant firm - competitive fringe" setting developed by Carlton and Perloff (2002) in the post-entry game. This extension aims at accounting for price taking behavior of "renewable" firm which represents the competitive fringe in real spot electricity market. The idea behind this extension is that in a stylized model with only two technologies competing in a spot market, the "traditional" generator sets the price knowing that it will face a competitive rival while the "renewable" producer receives the price chosen by the marginal "traditional" firm despite being competitive in its bid. This extension transforms the two stage game in a three stage game, in which the PV producer is a follower (competitive fringe) in the production game and a leader in the investment game due to the merit order rule. This extension reveals that even when the PV generator behaves as a competitive fringe in the spot market, it is able to influence equilibrium outcome to its own advantage through investment choices although to a smaller degree than in the standard setting.

The next step is to use the models to evaluate the relative desirability of policy tools which foster investments in renewable technologies, such as feed-in tariffs and/or partial subsidization of investment costs. The idea is to use a social welfare function to calculate the optimal feed-in tariff and the optimal rate of capacity investment subsidy. The effect of such policy interventions will be then evaluated also from a competitive point of view. We expect that this analysis will foster our understanding of competition in power generation and will provide us with useful policy recommendations.

Appendix A   Analytical calculations

A.1   Ex post analysis

The ex post pay-off of strategies B and C is calculated as:

$$\Pi_s = (a - bq_g - bxk_s)xk_s - I_s k_s \tag{42}$$

By substituting in previous equation the optimal values of k_s^C and k_s^B calculated as functions of x^* and the optimal quantity of firm G which is the minimum between its installed capacity and its optimal production given the electricity supplied by S, we obtain:

$$\Pi_s^B = \left(a - b\left(\frac{a - b\max(x,x^*)k_s^B - c - I_g}{2b}\right)\right)x\left(\frac{a + c + I_g}{3bx^*}\right) - \\ bx^2\left(\frac{a + c + I_g}{3bx^*}\right)^2 - I_s\left(\frac{a + c + I_g}{3bx^*}\right) \tag{43}$$

$$\Pi_s^C = \left(a - b\left(\frac{a - b\max(x,x^*)k_s^C - c - I_g}{2b}\right)\right)x\left(\frac{x^*(a + c + I_g) - 2I_s}{2bx^{*2}}\right) - \\ bx^2\left(\frac{x^*(a + c + I_g) - 2I_s}{2bx^{*2}}\right)^2 - I_s\left(\frac{x^*(a + c + I_g) - 2I_s}{2bx^{*2}}\right) \tag{44}$$

To calculate their expected value, we firstly use a generic probability density function, $P(x)$, defined for $x \in [0,1]$. The expected value of a generic function $f(x)$ can be rewritten as:

$$\mathbb{E}[f] = \int_0^1 f(x)P(x)dx \tag{45}$$

Expected profits are then:[18]

$$\mathbb{E}[\Pi_s^{B,C}] = \int_0^1 \Pi_{B,C}(x)P(x)dx \tag{46}$$

For strategy B we have:

$$\mathbb{E}[\Pi_s^B] = -\frac{AI_s}{3bx^*} - \frac{A}{18bx^{*2}}\int_0^1 (2Ax^2 - 3Axx^* - Ax\max(x,x^*))P(x)dx = \\ = -\frac{AI_s}{3bx^*} - \frac{A}{18bx^{*2}}\left(2A\int_0^1 x^2 P(x)dx - 3Ax^*\int_0^1 xP(x)dx - A\int_0^1 x\max(x,x^*)P(x)dx\right) = \\ -\frac{AI_s}{3bx^*} - \frac{A}{18bx^{*2}}\left(2A\mathbb{E}[x^2] - 3Ax^{*2} - AM\right)$$

where:

$$M = \int_0^1 x\max(x,x^*)P(x)dx \tag{47}$$

Simplifying:

$$\mathbb{E}[\Pi_s^B] = -\frac{AI_s}{3bx^*} - \frac{A^2 \mathbb{E}[x^2]}{9bx^{*2}} + \frac{A^2}{6b} + \frac{A^2 M}{18bx^{*2}} \tag{48}$$

For strategy C, let us firstly rewrite the profits as:

$$\Pi_s^C = \frac{I_s}{2bx^{*2}}(2I_s - Ax^*) - \frac{(2I_s - Ax^*)^2}{4bx^{*4}}x^2 + \frac{(2I_s - Ax^*)[(2I_s - Ax^*)\max(x,x^*) - 2Ax^{*2}]}{8bx^{*4}}x = \\ = \frac{I_s B}{2bx^{*2}} - \frac{B^2}{4bx^{*4}}x^2 + \frac{B^2\max(x,x^*) - 2ABx^{*2}}{8bx^{*4}}x$$

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[18]Note that we have dropped the subscript s for expositional convenience.

where $B = 2I_s - Ax^*$. The expected profits are:

$$\mathbb{E}[\Pi_s^C] = \frac{I_s B}{2bx^{*2}} - \int_0^1 \left(\frac{B^2}{4bx^{*4}} x^2 + \frac{B^2 \max(x, x^*) - 2ABx^{*2}}{8bx^{*4}} x \right) P(x) dx =$$

$$= \frac{I_s B}{2bx^{*2}} - \frac{B^2}{4bx^{*4}} \int_0^1 x^2 P(x) dx + \frac{B^2}{8bx^{*4}} \int_0^1 x \max(x, x^*) P(x) dx - \frac{AB}{4bx^{*2}} \int_0^1 x P(x) dx =$$

Using again the definition of M we obtain:

$$\mathbb{E}[\Pi_s^C] = \frac{I_s B}{2bx^{*2}} - \frac{AB}{4bx^*} - \frac{B^2}{4bx^{*4}} E[x^2] + \frac{MB^2}{8bx^{*4}} \tag{49}$$

Recalling that $\mathbb{E}[x] = x^*$, we may rewrite the expected profits of strategies B and C using the definition of variance of a random variable, $\mathrm{Var}[x] = \mathbb{E}[x^2] - \mathbb{E}[x]^2$. After some manipulations we get:

$$E[\Pi_B] = \frac{A^2}{18b} - \frac{AI_s}{3bx^*} + \frac{A^2}{18bx^{*2}}(M - 2\mathrm{Var}[x]) \tag{50a}$$

$$E[\Pi_C] = \frac{2I_s B - B^2}{4bx^{*2}} - \frac{AB}{4bx^*} + \frac{B^2}{8bx^{*4}}(M - 2\mathrm{Var}[x]) \tag{50b}$$

The condition for $E[\Pi_B] < E[\Pi_C]$ is therefore equivalent to:

$$\frac{A^2}{18} - \frac{AI_s}{3x^*} + \frac{A^2}{18x^{*2}}(M - 2\mathrm{Var}[x]) < \frac{B^2}{8x^{*4}}(M - 2\mathrm{Var}[x]) \tag{51}$$

If we call $I = 6I_s$, the previous inequality becomes:

$$\frac{A^2}{18} - \frac{AI}{18x^*} + \frac{A^2}{18x^{*2}}(M - 2\mathrm{Var}[x]) < \frac{(I/3 - Ax^*)^2}{8x^{*4}}(M - 2\mathrm{Var}[x]) \tag{52}$$

which we simplify by multiplying both sides by $\frac{18x^{*2}}{I^2}$:

$$\frac{A^2 x^{*2}}{I^2} - \frac{Ax^*}{I} + \frac{A^2}{I^2}(M - 2\mathrm{Var}[x]) < \frac{(1 - 3x^*A/I)^2}{4x^{*2}}(M - 2\mathrm{Var}[x]) \tag{53}$$

We call $\hat{x} = \frac{I}{A}$ in order to reduce the inequality to:

$$\frac{x^{*2}}{\hat{x}^2} - \frac{x^*}{\hat{x}} + \frac{1}{\hat{x}^2}(M - 2\mathrm{Var}[x]) < \frac{(1 - 3x^*/\hat{x})^2}{4x^{*2}}(M - 2\mathrm{Var}[x]) \tag{54}$$

Finally we call s the ratio $x^*/\hat{x}$ and we rewrite previous condition as:

$$s(s - 1) < \left(s^2 - \frac{(1 - 3s)^2}{4} \right) \frac{2\mathrm{Var}[x] - M}{\hat{x}^2} \tag{55}$$

By further simplification we obtain:

$$4s(s - 1) < (6s + 5s^2 - 1)\frac{2\mathrm{Var}[x] - M}{\hat{x}^2} \tag{56}$$

Appendix B   Three stage game

In this section we study the effect on equilibrium outcomes following a change in competition rules in post-investment stage. In particular, we adopt the "dominant firm - competitive fringe" setting developed by Carlton and Perloff (2002) to model competition in production between the "traditional" producer which represents the dominant firm and the "renewable" producer which behaves like a competitive fringe. This extension aims at accounting for price taking behavior of "renewable" firm in real spot electricity markets which are organized as a uniform price auction with all infra-marginal units receiving the system marginal price, i.e. the price bid by the last unit called into operation. The electricity from "renewable" plants is generally bid at zero, while the power from traditional technologies is offered at a positive price which must cover at least the marginal positive cost of production. Therefore, in a stylized model with only two technologies competing in a spot market, the "traditional" generator sets the price knowing that it will face a competitive rival while the "renewable" producer receives the price chosen by the dominant firm despite being competitive in its bid. The results of this analysis are extremely relevant because they show that "renewable" generators are able to influence short run market outcomes with their investment decisions and thanks to merit order rule although they do not make the price in real spot market.[19]

Let us call again S the PV power plant and G the CCGT power plant. Production levels are denoted by $q_i > 0$, $i = s, g$ and generation capacities by k_i, $i = s, g$. Investment cost per unit of capacity is $I_i > 0$, $i = s, g$. S has a convex production cost function for output levels below capacity, $F_s q_s + \frac{c_s}{2} q_s^2$, with $F_s, c_s > 0$, and linear investment cost function, $I_s k_s$. G has linear production and investment cost functions, $I_g k_g + c_g q_g$, with $c_g > 0$. Production above capacity is infinitely costly for both S and G. We assume that $F_s > I_g + c_g$, which means that firm G has the lower minimum average cost. It is further assumed that the availability of PV capacity for production depends on weather conditions. Therefore for each level of installed capacity k_s the available capacity is $x k_s$, where x is the realization of a random variable $X \in [0, 1]$. Firms know the continuous distribution function of the random variable X as well as its expected value, $\mathbb{E}[x] = x^*$. Firms face a linear inverse demand function, $p(Q) = a - bQ$, where $Q = q_s + q_g \subseteq (0, x k_s + k_g)$.

The structure of the game is the following. In the first stage firm S chooses its capacity, k_s: the investment is irreversible in the sense that capacity already installed cannot be dismissed. In the second stage firm G selects simultaneously its capacity, k_g, and its production level, q_g, knowing it that it will face a competitive fringe in the spot market.[20] In the third stage, S chooses its production possibly increasing its capacity prior to compete in the market. The game is solved by backward induction.

B.1   Third and second stage solutions

In the last stage of the game S chooses its optimal production level knowing that it may increase its capacity prior to compete in the spot market. As a price taker it sets its quantity by equating expected market price and expected marginal cost of production:

$$\mathbb{E}[a - b q_g - b q_s] = \mathbb{E}[MC(q_s, k_s)] \quad \text{where} \tag{57a}$$

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[19]See note 3.
[20]The same reasoning in footnote 10 applies.

$$MC(q_s, k_s) = \begin{cases} F_s + c_s q_s & \text{if } q_s \leq x^* k_s \\ \frac{I_s}{x} + F_s + c_s q_s & otherwise \end{cases} \tag{57b}$$

S reaction function is again a kinked curve whose shape depends on the investment decisions that have been taken in previous stages of the game. When the firm has already installed sufficient capacity, its costs in the last stage of the game only consist in production costs thus the first marginal cost curve applies. Conversely, when S's optimal choice of q_s in the last stage of the game is larger than the available capacity, i.e. $q_s > x^* k_s$, the firm must sustain also an investment cost to expand the capacity before producing. In this case the second marginal cost function is the relevant one.

Just like in the two stage game, it is possible to calculate the thresholds f q_g that make the PV producer switching from a reaction curve to another. We remark that the expected inverse demand function is decreasing in the quantity of electricity provided by firm G: $\mathbb{E}[a - bq_g - bq_s]$. We depict these curves for different values of q_g in Figure 15. Expected inverse demand curves such as ED_1 emerge when the quantity of electricity produced by G, q_g, is quite large. In this case expected inverse demand curves cross expected marginal cost function $F_s + c_s q_s$. By the same token, small quantities of q_g are associated to expected inverse demand curves such as ED_3 which cross expected marginal cost function at $F_s + \frac{I_s}{x^*} + c_s q_s$. In the intermediate case expected inverse demand curves cross expected marginal cost curve at the kink. Note that if q_g is very large, i.e. $q_g > \frac{a - F_s}{b}$, then $q_s = 0$.
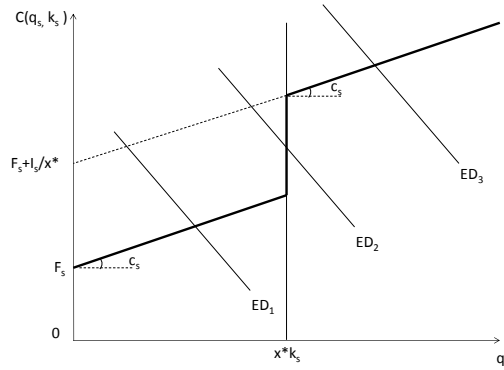
Figure 15: Expected inverse demand curves and marginal cost curves

Let us define:

- $q_g^h = \frac{a - (c_s + b)x^* k_s - F_s}{b}$ as the quantity of q_g such that, $\forall q_g > q_g^h$:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[F_s + c_s q_s] \tag{58a}$$

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g - F_s}{c_s + b} \tag{58b}$$

- $q_g^l = \frac{x^*[a - (c_s + b)x^* k_s - F_s] - I_s}{bx^*}$ as the quantity of q_g such that, $\forall q_g < q_g^l$:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[\frac{I_s}{x} + F_s + c_s q_s] \tag{59a}$$

$$R_s(q_g) = q_s = \frac{x^*(a - bq_g - F_s) - I_s}{(c_s + b)x^*} \tag{59b}$$

- $\forall q_g$ such that $q_g^l < q_g < q_g^h$, firm S produces at (available) capacity:

$$\bar{R}_s = q_s = x^* k_s \tag{60}$$

Firm S reaction function has the same shape as the one depicted in Figure 2 with q_g^h and q_g^l corresponding to the new thresholds. Figures 16 to 19 show all the possible equilibria in the last stage of the game according to the value of k_s installed by S in the first stage. We analyze all possible situations to find the subgame perfect Nash equilibrium.
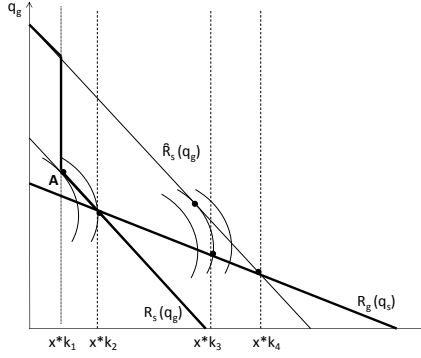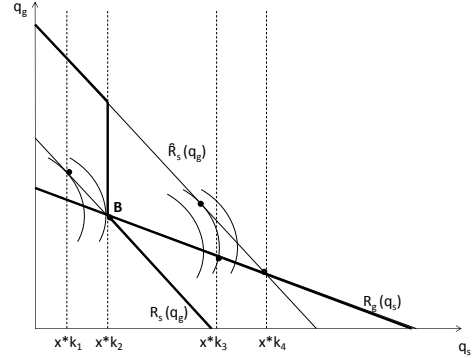

Figure 16: $x^* k_s \leq x^* k_s^A$

Figure 17: $x^* k_s = x^* k_s^B$

Figure 18: $x^* k_2 < x^* k_s \leq x^* k_3$
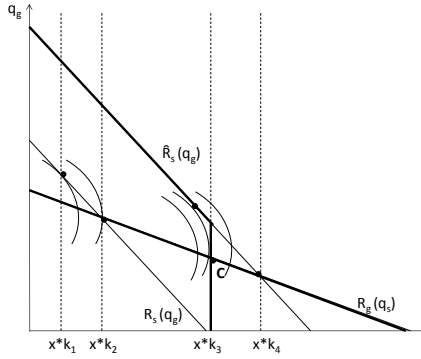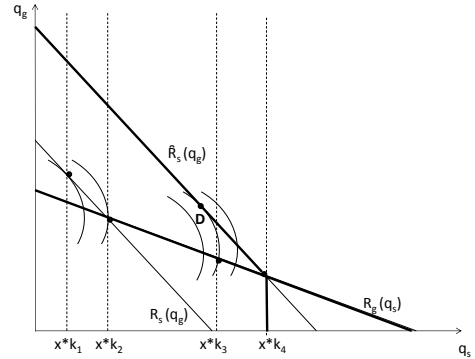

Figure 19: $x^* k_s > x^* k_3$

B.1.1 Cases A and B: very small and small photovoltaic capacity

When S has built a small capacity in the first stage of the game it may decide to increase it in the last stage. However in this case it should bear a new investment cost. The optimal quantity of electricity to be produced is selected by equating the expected inverse demand function and S marginal cost function which includes investment cost:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}\left[\frac{I_s}{x} + F_s + c_s q_s\right] \tag{61}$$

The optimal q_s is calculated as a function of q_g:

$$q_s = \frac{x^*(a - bq_g - F_s) - I_s}{(c_s + b)x^*} \tag{62}$$

In the second stage, firm G sets its optimal capacity and production. In this setting it behaves as a Stackelberg leader which maximizes its profit over the inverse residual demand, i.e. the inverse market demand minus the supply of the PV producer. G chooses its quantity as the solution to the following maximization problem:

$$\underset{q_g, k_g}{\text{Max}} \quad \mathbb{E}[\Pi_g] = \mathbb{E}[p^d(q_g)q_g - cq_g - I_g k_g] \quad \text{subject to}$$
$$q_g \leq k_g \tag{63}$$

where:

$$p^d = \frac{ac_s x^* + b[I_s + (F_s - c_s q_g)x^*]}{(c_s + b)x^*} \tag{64}$$

At the optimimum the constraint is binding and G installs and produces the quantity:

$$k_g^A = q_g^A = \frac{c_s(a - c_g - I_g)x^* + b[I_s + (F_s - c_g - I_g)x^*]}{2bc_s x^*} \tag{65}$$

By substituting G's optimal quantity in equations (62) and (64), we obtain S's optimal quantity and equilibrium price from which we can calculate firms' profits:

$$q_s^A = \frac{c_s(Ax^* - 2I_s) - b(Bx^* + I_s)}{2c_s(c_s + b)x^*} \tag{66a}$$

$$p^A = \frac{c_s Cx^* + b(I_s + Dx^*)]}{2(c_s + b)x^*} \tag{66b}$$

$$\Pi_s^A = \frac{[c_s(Ax^* - 2I_s) - b(Bx^* + I_s)]^2}{8c_s(c_s + b)^2 x^{*2}} \tag{66c}$$

$$\Pi_g^A = \frac{[c_s Ex^* + b(Bx^* + I_s)]^2}{4bc_s(c_s + b)x^{*2}} \tag{66d}$$

where:

$$A = a + c_g - 2F_s + I_g = E - 2B > 0$$
$$B = F_s - c_g - I_g > 0$$
$$C = a + c_g + I_g > 0$$
$$D = c_g + I_g + F_s > 0$$
$$E = a - c_g - I_g > 0$$

This equilibrium corresponds to point A in Figure 16 and arises in the third stage of the game if in the earlier stage firm S has installed:

$$k_s^A \leqslant \frac{c_s(Ax^* - 2I_s) + b(Bx^* - I_s)}{2c_s(c_s + b)x^{*2}} \tag{68}$$

When in the first stage of the game S has invested in a capacity which is larger

than k_s^A but still smaller than its optimal choice of production, the firm continues to compete with a reaction function which includes investment cost. In this case the leadership in production of firm G is somehow constrained because the firm should take into account that equilibrium A is unattainable. Therefore to find its optimal quantity and capacity it maximizes its profits over the residual demand as in eq. (63): each time the residual demand will be the difference between the market demand and the quantity of electricity provided by S, $q_s = x^* ks$. This equilibrium occurs in a point on the right portion of the segment A-B in Figures 16 and 17 (excluding point A).[21]

If in the earlier stage S has installed the Cournot capacity the tangency point occurs in B (Figure 17) and the optimal response of firm G is to produce exactly Cournot. In this case, the equilibrium outcome is:

$$q_s^B = \frac{Ax^* - 2I_s}{(2c_s + b)x^*} \tag{69a}$$

$$q_g^B = \frac{c_s E x^* + b(Bx^* + I_s)}{b(2c_s + b)x^*} \tag{69b}$$

$$p^B = \frac{c_s C x^* + b(I_s + F_s x^*)}{(2c_s + b)x^*} \tag{69c}$$

$$\Pi_s^B = \frac{c_s(Ax^* - 2I_s)^2}{2(2c_s + b)^2 x^{*2}} \tag{69d}$$

$$\Pi_g^B = \frac{[c_s E x^* + b(Bx^* + I_s)]^2}{b(2c_s + b)^2 x^{*2}} \tag{69e}$$

This equilibrium arises if S has installed in the first stage:

$$k_s^B = \frac{Ax^* - 2I_s}{(2c_s + b)x^{*2}} \tag{70}$$

B.1.2 Cases C and D: large and very large photovoltaic capacity

If the photovoltaic producer has installed a large capacity in the first stage of the game, its choice of quantity in the third stage will depend only on production costs. In this case, firm S chooses its optimal quantity as the solution to the equation:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[F_s + c_s q_s] \tag{71}$$

which gives the quantity q_s as a function of q_g:

$$q_s = \frac{a - bq_g - F_s}{c_s + b} \tag{72}$$

In the second stage of the game the leader in production, firm G, sets its output and its capacity to maximize profits over the residual demand. The problem is the same as in eq. (63) but in this case the residual demand is equal to:

$$p^d = \frac{bF_s + c_s(a - bq_g)}{c_s + b} \tag{73}$$

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[21]The equilibrium is the tangency point between the isoprofit curve of G associted to the highest profit and S reaction function including investment cost.

At the optimimum G installs and produces:

$$k_g^D = q_g^D = \frac{c_s E + bB}{2c_s b} \tag{74}$$

Again, by substituting G's optimal quantity in equations (71) and (72), we obtain S's optimal quantity, equilibrium price and profits:

$$q_s^D = \frac{c_s A - bB}{2c_s(c_s + b)} \tag{75a}$$

$$p^D = \frac{c_s C + bD}{2(c_s + b)} \tag{75b}$$

$$\Pi_s^D = \frac{[c_s A - bB]^2}{8c_s(c_s + b)^2} \tag{75c}$$

$$\Pi_g^D = \frac{[c_s E + bB]^2}{4c_s b(c_s + b)} \tag{75d}$$

This equilibrium is represented as point D in Figure 19. By constructing the isoprofit curve of G passing through the equilibrium point D we see that it meets firm G reaction function in point C (Figure 18). The coordinates of such point are:

$$q_s^C = \frac{E\sqrt{c_s(c_s + b)} - c_s E - bB}{b\sqrt{c_s(c_s + b)}} \tag{76a}$$

$$q_g^C = \frac{c_s E + bB}{2b\sqrt{c_s(c_s + b)}} \tag{76b}$$

This point ensures to G the same profits of equilibrium D while through the demand function we can calculate the market price and profits of S:

$$p^C = \frac{bB + c_s E + 2\sqrt{c_s(c_s + b)}(c_g + I_g)}{2\sqrt{c_s(c_s + b)}} \tag{77}$$

$$\Pi_s^C = \frac{\left\{\left[c_s - \sqrt{c_s(c_s + b)}\right]E + bB\right\}\left\{\left[c_s^2 - c_s\sqrt{c_s(c_s + b)}\right]E + b^2 B + b\left[c_s H - 2\sqrt{c_s(c_s + b)}B\right]\right\}}{2b^2 c_s(c_s + b)} \tag{78}$$

where:

$$H = a - 2c_g + F_s - 2I_g$$

Equilibrium D is preferred by CCGT producer when in the first stage S has installed:

$$k_s > \frac{q_s^C}{x^*} = \frac{E\sqrt{c_s(c_s + b)} - c_s E + bB}{x^* b\sqrt{c_s(c_s + b)}} \tag{79}$$

while for $k_s = \frac{q_s^C}{x^*}$ firm G prefers the equilibrium at point C.

B.1.3 Case E: intermediate photovoltaic capacity

When in the third stage of the game firm S produces at available capacity, firm G is constrained to behave as a Stackelberg follower.[22] Gas producer's reaction function is the same as the one calculated in the standard setting:

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[22]Which means that the first mover advantage in production of firm G is completely lost.

$$R_g(k_s) = q_g^E = \frac{a - bx^* k_s - c_g - I_g}{2b} \tag{80}$$

Equilibrium price and profits in implicit form are:

$$p^E = \frac{a - bx^* k_s + c_g + I_g}{2} \tag{81a}$$

$$\Pi_s^E = \left(\frac{a - bx^* k_s + c_g + I_g}{2} - F_s - \frac{c_s x^* k_s}{2} \right) x^* k_s \tag{81b}$$

$$\Pi_g^E = \frac{(a - bx^* k_s - c_g - I_g)^2}{4b} \tag{81c}$$

B.2   First stage solutions

To find an explicit form for the equilibrium in case E, we solve the first stage of the game in which S defines its optimal capacity k_s by maximizing its expected profits:

$$\underset{k_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E} \left[p(xk_s, q_g)xk_s - \left(\frac{I_s}{x} + F_s + \frac{c_s xk_s}{2} \right) xk_s \right] \tag{82}$$

Using the reaction function of G and calculating the FOC of the problem, we get equilibrium capacity, quantities, price and profits in explicit form:

$$k_s^E = \frac{Ax^* - 2I_s}{2(c_s + b)x^{*2}} \tag{83a}$$

$$q_s^E = \frac{x^* A - 2I_s}{2(c_s + b)x^*} \tag{83b}$$

$$q_g^E = \frac{x^* \{b[a - 3(c_g + I_g) + 2F_s] + 2c_s E\} + 2bI_s}{4b(c_s + b)x^*} \tag{83c}$$

$$p^E = \frac{x^* [b(a + c_g + I_g + 2F_s) + 2c_s C] + 2bI_s}{4(c_s + b)x^*} \tag{83d}$$

$$\Pi_s^E = \frac{[Ax^* - 2I_s]^2}{8(c_s + b)x^{*2}} \tag{83e}$$

$$\Pi_g^E = \frac{\{x^* \{b[a - 3(c_g + I_g) + 2F_s] + 2c_s E\} + 2bI_s\}^2}{16b(c_s + b)^2 x^{*2}} \tag{83f}$$

B.3   Optimal strategy selection

Let us firstly qualitatively discuss the possible outcomes of the game with the help of Figures 16 to 19. The graphics reveal that, when the "renewable" generator prefers to postpone investments and hence presents in the last stage the inner reaction function, between point A in Figure 16 and point B in figure 17, it will surely prefers the latter equilibrium. Hence the strategy leading to equilibrium A is always dominated by the strategy corresponding to equilibrium B. Likewise, when the "renewable" generator anticipates investments in the first stage of the game and competes in the last stage with the outer reaction function, between equilibrium C in Figure 18 and equilibrium D in Figure 19 it will always prefer equilibrium at point C. Therefore, although the PV producer is the follower in the production game, it can eliminate strictly dominated strategies leading to points such as A and D at the beginning of the game exploiting

its first mover advantage in the investment game. It thus selects its optimal capacity investment on the segment B-C as it does in the two stage game on the segment A-B. The strategic incentives depending on merit order rule still hold. The only difference here is in that the segment B-C is shorter than the segment A-B, which constraints the set of possible capacity choices.

Analytically, firm S selects its optimal strategy by comparing the net profits from each of the five cases, regardless if the investment has been paid in the first or the third stage of the game. As in the baseline model we indicate net profits with a * to distinguish them from gross profits:[23]

$$\Pi_s^{A^*} = \frac{[c_s(Ax^* - 2I_s) - b(Bx^* + I_s)]^2}{8c_s(c_s + b)^2 x^{*2}} \tag{84a}$$

$$\Pi_s^{B^*} = \frac{c_s(Ax^* - 2I_s)^2}{2(2c_s + b)^2 x^{*2}} \tag{84b}$$

$$\Pi_s^{C^*} = \frac{\left\{(c_s + b)\left[c_s - \sqrt{c_s(c_s + b)}\right]E + bB\right\}\left\{\left[c_s^2 - c_s\sqrt{c_s(c_s + b)}\right]Ex^* - b\left[\sqrt{c_s(c_s + b)}Bx^* - 2c_s(I_s + Bx^*)\right]\right\}}{2b^2[c_s(c_s + b)]^{\frac{3}{2}}x^*} \tag{84c}$$

$$\Pi_s^{D*} = \frac{(c_sA - bB)\left[(c_sA - bB)x^* - 4(c_s + b)I_s\right]}{8c_s(c_s + b)^2 x^*} \tag{84d}$$

$$\Pi_s^{E^*} = \frac{[Ax^* - 2I_s]^2}{8(c_s + b)x^{*2}} \tag{84e}$$

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[23]Note that $\Pi_s^A = \Pi_s^{A^*}$, $\Pi_s^B = \Pi_s^{B^*}$ and $\Pi_s^E = \Pi_s^{E^*}$.

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