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Competition between renewable and traditional power producers: how spot market design influences the emergence of strategic investments in renewable capacity

Silvia Concettini [1],

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[1] IRJI, Université de Tours, Chair Energy and Prosperity.

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Competition between renewable and traditional power producers: how spot market design influences the emergence of strategic investments in renewable capacity

Silvia Concettini

IRJI, Université de Tours
Chair Energy and Prosperity

Abstract

We introduce a theoretical framework for the analysis of competition between a traditional and a renewable generator in a spot electricity market where the electricity from renewable sources is always the first to be dispatched. The model accounts for randomness in the availability of renewable capacity due to the partial unpredictability of weather conditions. Competition is studied through a model of strategic investments for entry deterrence with two post entry competition settings: the Cournot framework in a two stage game and the dominant firm-competitive fringe setting in a three stage game. Both models show that the renewable producer exploits merit order rule by strategically investing in a large generation capacity in order to crowd out the production of its rival. The analysis has important implications for electricity market design.

Keywords: Electricity markets, renewable generation, merit order, capacity investments
JEL classification: D43, L13, L43, L94

1. Introduction

Generators' behaviour in liberalized electricity markets has been extensively analyzed within different theoretical frameworks of imperfect competition (see for instance, Green and Newbery, 1992; von der Fehr and Harbord, 1993; Federico and Rahman, 2003; Murphy and Smeers, 2005; Fabra et al., 2006; Fabra et al., 2011). During last years, competition in generation has been substantially animated by new entrants investing in renewable technologies. In 2014, 79.1% of total 26.9 GW of new capacity installed in European Union has been renewable; moreover the 2014 has been the seventh year that renewable installations have represented over 55% of all additional power capacity built in the EU (Source: Eurostat). Much of this technological shift may be attributed to the approval of 2009 Climate and Energy Package establishing compulsory targets for Member States in terms of renewable endowment. Despite the massive entry of renewable generators, the study of interactions between traditional and renewable power producers in the context of spot electricity markets remains an almost unexplored field of research from a theoretical point of view (Milstein and Tishler, 2011), while it has attracted significant empirical interest (Cutler et al., 2011; Wurzburg at al., 2013; Jónsson et al., 2010; Ketterer, 2014; O'Mahoney and Denny, 2011; Clo et al., 2015; Gelabert et al., 2011).

This article 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.[1] 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 may impact investment preferences and it significantly influences system security. Concerning trade,

[1]We restrict our analysis to the case in which the entry of renewable generators is profitable. The study of the impact of support mechanisms on the entry of renewable producers is behind the scope of this paper. For a general discussion on this topic see Couture and Gagnon (2010). Support mechanisms are not considered because the analysis focuses on the strategic incentives to invest in renewable capacity determined by electricity market design. These incentives may be strengthen by support schemes but they hold also in their absence (which will be the most likely situation in the next future).

the setting considers that spot electricity markets are organized on the basis of the merit order rule. The merit order is a way of ranking available sources of generation in ascending order of their variable cost; given that electricity from renewable sources has zero or negligible variable production costs, it is always the first in the merit order ranking followed by higher variable cost technologies.

The competition between a traditional and a renewable power producer is examined through a modified version of the *Dixit model* for entry deterrence (Dixit, 1980) with two post entry competition settings: the Cournot framework in a two stage game and the dominant firm-competitive fringe setting (Carlton and Perloff, 1994) in a three stage game. In the first model the renewable producer enjoys some market power while in the second one it behaves competitively. The two settings aims at reproducing two alternative market designs for renewable generators' participation in the spot market: on the one hand the production from several power plants may be aggregated by a unique entity;[2] on the other hand, the supply from renewable sources may be more fragmented. The choice of this particular theoretical framework stems from three reasons.

Real spot markets are organized as uniform price auctions. 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. Market equilibrium is determined by the intersection of supply and demand schedule. The firms that are called into operation are all paid the system marginal price which corresponds to highest accepted bid. Because of merit order rule the power from renewable sources is always the first to be brought online in spot electricity markets.[3] As in a standard *Dixit model* the profitability of entry depends on the capacity choices made by the incumbent in previous stages, the profitability of investments in traditional technologies for power generation rests on the size of the residual demand, which in turn is determined by the capacity installed by the renewable producer. In our model the renewable power plant is thus the incumbent and the

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

[3] It is worthy to note that the market operator does not know the true variable cost of each producer and the market supply schedule is built on the basis of bids. Although the bid of each operator does not necessarily correspond to its true variable cost, the supply schedule defined on price bids tend to respect the merit order ranking based on variable costs. For an analysis of strategic bidding in spot electricity market see instead Fabra et al., 2011.

traditional producer is the entrant in the capacity game.

Second, the *Dixit model* is sufficiently flexible to allow the introduction of a certain degree of uncertainty about demand and/or cost functions (Maskin, 1997). Finally, this model allows for several types of competition in the post entry game: firms may play in a perfect competitive setting (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). Although in real power markets firms compete in price, in a stylized model with a traditional and a renewable producer, firms rather play a quantity game since the renewable power plant can always bid at zero due to its cost advantage, leaving the residual demand to the traditional producer. Quantity competition presents the additional advantage that both firms receive the same price as in a uniform price auction; moreover from a theoretical point of view this setting is suitable for firms competing in price but having capacity constraints (Kreps and Scheinkman, 1983).

In both settings merit order rule confers a first mover advantage to the renewable producer. In the first model, the renewable producer behaves as a Stackelberg leader in the investment game in order to modify competition in production to its own advantage. The optimal choice of renewable capacity is not influenced by the expected value of capacity availability. However, according to the value of this parameter merit order rule may lead to an equilibrium in which both renewable producer and consumers are better off if the investment cost in the renewable technology is relatively small. In this case, a public intervention which further reduces the investment cost increases the likelihood of this market outcome. Furthermore, when the forecast of the expected value of capacity availability is subject to some errors and the investment cost in the renewable technology is relatively small, even larger capacity investments in the renewable technology may result. Similar insights may be drawn from the three stage game where some reasonable assumptions on parameters' values must be introduced. Even if the renewable producer behaves competitively in the last stage of the game, it still has an incentive to modify competition in production through strategic investments although to a smaller degree.

This analysis has important implications for electricity market design. The empirical literature has shown that a larger renewable supply on the spot market has generated a displacement of higher variable cost production in the merit order ranking, significantly reducing the production of traditional technologies. This will have relevant consequences in the long run on system reliability as the old power plants must be replaced with new ones. The incentives for investments in traditional/back up facilities must be restored to compensate the negative effects on production determined by merit order rule, a recent proposal being, among others, the creation of capacity markets alongside "energy-only" markets. A thorough understanding of competition mechanisms between different types of generators in the context of spot electricity market seem therefore fundamental not only to possibly improve market design in the light of recent environmental concerns and technological changes but also to intervene on supporting schemes for renewable technologies.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 and 4 are dedicated to the two stage game and its resolution. Section 5 explores the implications of extending the basic setting to a three stage game. Section 6 concludes with a discussion on the policy implications of the analysis.

2. Literature review

The literature on competition in liberalized power markets may be divided in two strands: a first strand investigates bidding behaviour of generators in spot electricity markets (short-run performances); a second one studies the links between spot market design and incentives to invest in generation capacity (long-run performances). 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.[4]

[4]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).

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; 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). The major limit of this approach for our research purpose 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 (von der Fehr and Harbord, 1998). However this model provides a formal justification for the elimination of marginal cost bidding strategy in a Bertrand setting when capacity is constrained.[5] 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 scarce.

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

[5]This result is similar to auction model's prediction.

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.[6] 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 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.[7]

In the same vein, Murphy and Smeers (2005) study capacity investments when a base load and

[6]For a theoretical analysis of such games see Gabszewicz and Poddar (1997).

[7]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.

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.[8] 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. 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.[9]

[8] 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).

[9] The concept of average cost may be associated to that of "Levelized Cost of Electricity (LCOE)" which is a commonly used instrument to compare costs for unit of electricity generated from different sources. The LCOE 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 2014 Annual Energy

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 xk_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, $p(Q) = a - bQ$, with $a,b > 0$, where $Q = q_s + q_g \subseteq (0, xk_s + k_g)$.[10]

The structure of the game is the following. In the first stage the firm S chooses its capacity investment, k_s; the investment is irreversible in the sense that capacity already installed cannot be dismissed in the following stage. In the second stage 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 renewable 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). The game is solved by backward induction to find the sub-game perfect Nash equilibrium.

Outlook, the dollar cost (before subsidy) per megawatt-hour of a conventional combined cycle plant entering in service in 2019 is 66,3 dollars while for a solar photovoltaic plant is 130 dollars (IEA, 2014).

[10]Feed-in tariff schemes are a commonly adopted policy mechanism designed to accelerate investments in renewable technologies. 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. In our setting, the tariff is not considered but we may consider a support policy for which an amount τ is awarded to the PV producer for each unit of installed capacity. The tariff reduces the true investment cost in the renewable technology (I_{pv}) which is deemed so high so as to make entry unprofitable, i.e. $I_{pv} > a$. Therefore the tariff verifies the following inequality, $I_{pv} - \tau = I_s < a$. In this case the role of feed-in tariff would be to make profitable the adoption of PV technology and favor the entry of renewable producers without modifying the main main insight of the model.

3.1. Second and first stage solutions

In the second stage of the game G selects production and capacity which maximize its expected profit:[11]

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

At the optimum the constraint is binding given that capacity and production are simultaneously selected by G and the firm would never invest in a capacity it cannot use for production. For each equilibrium we only report the quantity produced by G, knowing that the capacity is sized accordingly. In reality most of the capacity investments in CCGT power plants are already sunk; therefore this stage of the game may be interpreted as the one in which the traditional firm only adjusts its production. The 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:

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

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

S's reaction function is depicted in Figure 1. Note that the investment cost displaces the reaction function inward.

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

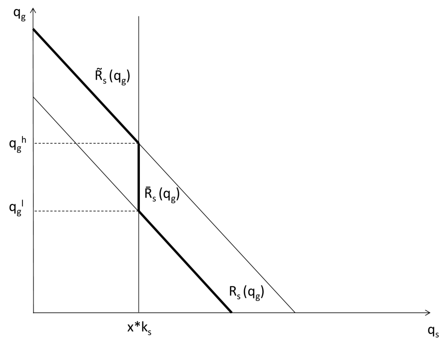


Figure 1: *S* reaction function

$\tilde{R}_s(q_g)$: reaction function without investment cost

$R_s(q_g)$: reaction function with investment cost

$\bar{R}_s$: reaction function when *S* is producing at available capacity

The thresholds of q_g which make *S* to switch from a cost curve to another are:

1. $\forall q_g > q_g^h = \frac{a-2bx^*k_s}{b}$, the relevant portion of *S*'s reaction function is:

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g}{2b} \tag{4}$$

   If *S* selects in the second stage of the game a production level which is below or equal to the available capacity, the production in the last stage is costless given that the investment has been already paid in the first stage;

2. $\forall q_g < q_g^l = \frac{x^*(a-2bx^*k_s)-I_s}{bx^*}$ the relevant portion of of *S*'s reaction function is:

$$R_s(q_g) = q_s = \frac{x^*a - bx^*q_g - I_s}{2bx^*} \tag{5}$$

   If *S* selects in the second stage a production level above the available capacity, it has to pay an additional investment and the reaction function moves inward;

3. $\forall q_g$ such that $q_g^l < q_g < q_g^h$, firm *S* produces at the expected value of available capacity:

$$\bar{R}_s = q_s = x^*k_s \tag{6}$$

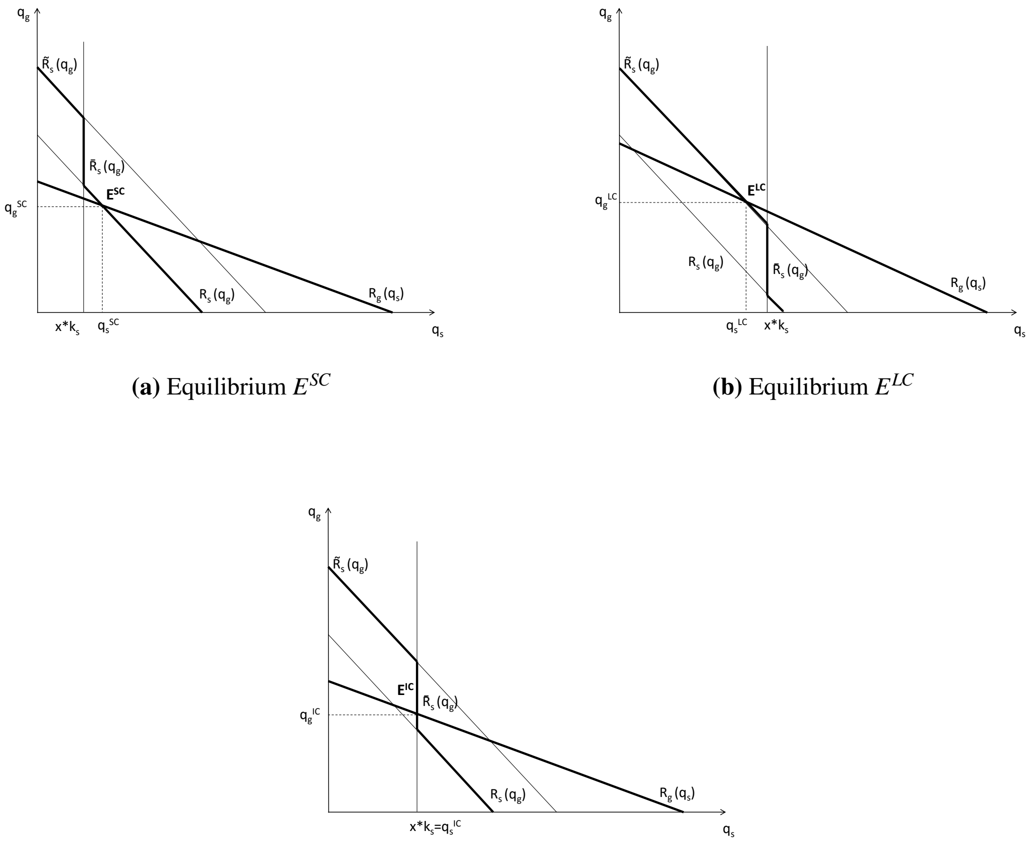
The following proposition describes the possible strategies for firm S in the first stage of the game and characterizes the corresponding game equilibrium.

Proposition 1. *In the first stage of the game S may choose to invest in a Small (SC), Large (LC) or Intermediate (IC) capacity. According to the capacity installed by S in the first stage, the game has the following three equilibria:*[12]

Equilibrium $\mathbf{E^{SC}}$ (Small capacity)	**Equilibrium $\mathbf{E^{LC}}$ (Large capacity)**	**Equilibrium $\mathbf{E^{IC}}$ (Intermediate capacity)**
$k_s^{SC} \leq \frac{x^*(a+c+I_g)-2I_s}{3bx^{*2}}$	$k_s^{LC} \geq \frac{a+c+I_g}{3bx^*}$	$k_s^{IC} = \frac{x^*(a+c+I_g)-2I_s}{2bx^{*2}}$
$q_s^{SC} = \frac{x^*(a+c+I_g)-2I_s}{3bx^*}$	$q_s^{LC} = \frac{a+c+I_g}{3b}$	$q_s^{IC} = \frac{x^*(a+c+I_g)-2I_s}{2bx^*}$
$q_g^{SC} = \frac{x^*[a-2(c+I_g)]+I_s}{3bx^*}$	$q_g^{LC} = \frac{a-2(c+I_g)}{3b}$	$q_g^{IC} = \frac{x^*[a-3(c+I_g)]+2I_s}{4bx^*}$
$p^{SC} = \frac{x^*(a+c+I_g)+I_s}{3x^*}$	$p^{LC} = \frac{a+c+I_g}{3}$	$p^{IC} = \frac{x^*(a+c+I_g)+2I_s}{4x^*}$
$\Pi_s^{SC} = \frac{[x^*(a+c+I_g)-2I_s]^2}{9bx^{*2}}$	$\Pi_s^{LC} = \frac{(a+c+I_g)[(a+c+I_g)x^*-3I_s]}{9bx^*}$	$\Pi_s^{IC} = \frac{[x^*(a+c+I_g)-2I_s]^2}{8bx^{*2}}$
$\Pi_g^{SC} = \frac{\{x^*[a-2(c+I_g)]+I_s\}^2}{9bx^{*2}}$	$\Pi_g^{LC} = \frac{[a-2(c+I_g)]^2}{9b}$	$\Pi_g^{IC} = \frac{\{x^*[a-3(c+I_g)]+2I_s\}^2}{16bx^{*2}}$

The equilibria corresponding to the three available strategies are sketched in Figure 2.

[12] The subscript refers to the player (s or g) while the superscript to the strategy selected by the PV producer.



(a) Equilibrium E^{SC}

(b) Equilibrium E^{LC}

(c) Equilibrium E^{IC}

Figure 2: Graphic representation of game's equilibria following S first stage capacity choice

(a) Equilibrium when S instals a Small capacity

(b) Equilibrium when S instals a Large capacity

(c) Equilibrium when S instals an Intermediate capacity

PROOF. If firm S has installed a Small capacity in the first stage, it may decide to increase it in the last stage. In this case, Nash equilibrium occurs where the reaction function of G crosses the portion of S reaction function including the investment cost, i.e. the inner reaction function $R_s(q_g)$. The solution is the usual Cournot-Nash equilibrium. S chooses its optimal quantity as the solution to the profit maximization problem:

$$\underset{q_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}\left[p(q_s, q_g)q_s - \left(\frac{I_s}{x}\right)q_s\right] \tag{7}$$

S optimal response is:

$$R_s(q_g) = q_s = \frac{x^*a - bx^*q_g - I_s}{2bx^*} \tag{8}$$

Combining S and G reaction functions, we obtain equilibrium quantities, price and profits for the equilibrium E^{SC}. The standard Cournot Nash equilibrium arises in the second stage of the game if in the first stage S has installed:[13]

$$k_s^{SC} \leqslant \frac{q_s^{SC}}{x^*} = \frac{x^*(a+c+I_g) - 2I_s}{3bx^{*2}} \tag{9}$$

If firm S has installed a Large capacity in the first stage, it presents a cost advantage relative to G in second 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 problem:

$$\underset{q_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}[p(q_s, q_g)q_s] \tag{10}$$

yielding the reaction function:

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g}{2b} \tag{11}$$

Combining S and G reaction functions we obtain the quantities, price and profits of equilibrium E^{LC}. When S has installed a Large capacity, the profit calculated as solution of the second stage of the game without considering the investment made in the first stage differs from the overall game profit and it is equal to $\frac{(a+c+I_g)^2}{9b}$, from which the total investment must be subtracted yielding Π_s^{LC}. This equilibrium arises if firm S has installed in the first stage of the game:[14]

$$k_s^{LC} \geqslant \frac{q_s^{LC}}{x^*} = \frac{a+c+I_g}{3bx^*} \tag{12}$$

When S's capacity size is between the thresholds determining equilibria E^{SC} and E^{LC}, S produces at available capacity, i.e. $q_s = x^*k_s$, and firm G behaves as a Stackelberg follower reacting to the quantity produced by its rival. We can rewrite G's reaction function (eq. 2) as a function of k_s:

$$R_g(k_s) = q_g^{IC} = \frac{a - bx^*k_s - c - I_g}{2b} \tag{13}$$

[13] Note that $q_s^{SC} > 0$ if $a > \frac{I_s}{x^*} - c - I_g$. Hence in this equilibrium, S chooses its quantity as min $\{0; q_s^{SC}\}$.

[14] Note that $\Pi_g^{LC} > 0$ if $a > 2(c+I_g)$. If $\Pi_g^{LC} < 0$ firm G prefers not to produce, so we shall exclude this opportunity.

We solve the first stage of the game in which S chooses k_s so as to maximize its expected profits coming from the Intermediate capacity strategy:

$$\underset{k_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}[p(xk_s, q_g)xk_s - I_s k_s] \tag{14}$$

Through the FOC of the problem we get the quantities, price and profits of equilibrium E^{IC}. This solution arises if S instals in the first stage of the game the following capacity:

$$k_s^{IC} = \frac{x^*(a+c+I_g) - 2I_s}{2bx^{*2}} \tag{15}$$

■

3.2. Optimal strategy selection

The renewable producer compares the pay-offs of each equilibrium to select its optimal strategy. The sub-game perfect Nash equilibrium is characterized in Proposition 2.

Proposition 2. *Investing in Intermediate capacity is the preferred strategy for the renewable producer as it dominates:*

- *the strategy of investing in Small capacity $\forall x^*$;*
- *the strategy of investing in Large capacity:*

  1) $\forall x^*$ when $\hat{x} > 1$ (Relatively large PV investment cost)

  2) for $x^* \neq \hat{x}$ when $\hat{x} \leq 1$ (Relatively small PV investment cost)

where:

$$\hat{x} = \frac{6I_s}{a+c+I_g} \tag{16}$$

For relatively small PV investment cost (case 2) when $x^* = \hat{x}$, investing in Intermediate and Large capacity yields exactly the same payoffs ($\Pi_s^{IC} = \Pi_s^{LC}$) and S is indifferent between the two strategies.

PROOF. The renewable producer always prefers to invests more in the first stage of the game rather than to postpone investments to the second stage. It is straightforward to verify that the following inequality holds for any value of x^* given the smaller denominator in Π_s^{IC}:

$$\Pi_s^{IC} = \frac{[x^*(a+c+I_g)-2I_s]^2}{8bx^{*2}} > \frac{[x^*(a+c+I_g)-2I_s]^2}{9bx^{*2}} = \Pi_s^{SC}\ , \forall x^* \tag{17}$$

When choosing between investing in an Intermediate or Large capacity, the PV producer picks the first strategy when the following inequality holds:

$$\Pi_s^{IC} = \frac{[x^*(a+c+I_g)-2I_s]^2}{8bx^{*2}} > \frac{(a+c+I_g)[(a+c+I_g)x^*-3I_s]}{9bx^*} = \Pi_s^{LC} \tag{18}$$

Given that both b and x^* are positive the condition boils down to:

$$[(a+c+I_g)x^*-6I_s]^2 > 0 \tag{19}$$

which, according to parameters' value, is verified:

$$\text{Case 1 (Relatively large PV investment cost):} \quad \hat{x} = \tfrac{6I_s}{a+c+I_g} > 1 \quad \Rightarrow \forall\ x^* \tag{20}$$

$$\text{Case 2 (Relatively small PV investment cost):} \quad \hat{x} = \tfrac{6I_s}{a+c+I_g} \leq 1 \quad \Rightarrow \text{for}\, x^* \neq \hat{x} \tag{21}$$

From eq. (19) it is possible to verify that when $\hat{x} \leq 1$ and $x^* = \hat{x}$, $\Pi_s^{IC} = \Pi_s^{LC}$. ■

Proposition 2 suggests that because of merit order rule, the renewable producer has a strategic incentive to increase its capacity size in order to crowd-out the production of its rival. The renewable producer may therefore use its choice in the capacity game to distort competition in the production game to its own advantage. Interestingly, the best strategy for firm S does not depend on parameters values and notably on the intermittency of the production represented by the expected value of capacity availability, x^*. When the investment cost in the renewable technology is relatively small and the expected value of capacity availability exactly equals $\hat{x}$, S may be even decide to invest in a larger capacity given that the Intermediate and Large capacity strategies yield the same pay-off. This result is summarized in the following Corollary.

Corollary 1. *The choice of the renewable producer to invest in a larger capacity than a standard one shot Cournot game would suggest is optimal independently from parameters values and in particular from the intermittency (the expected value of capacity availability).*

3.3. Consumer surplus analysis

Let us now analyze the impact of renewable producer optimal choices on consumer surplus.[15] The consumer surplus in E^{LC} and E^{IC} are respectively:

$$CS^{LC} = \frac{(c+I_g-2a)^2}{18b} \tag{22a}$$

$$CS^{IC} = \frac{[x^*(c+I_g-3a)+2I_s]^2}{32bx^{*2}} \tag{22b}$$

Consumers rank the two equilibria according to parameters values. Interestingly for some ranges of the parameters the interests of the renewable producer and the consumers may be aligned and they may agree on their preferred equilibrium. This result is pointed out in the following corollary.

Corollary 2. *When the investment cost in the PV technology is relatively large* $(\hat{x} > 1)$*, the interest of consumers and PV producer always diverge. However, when the investment cost in the PV technology is relatively small* $(\hat{x} \leq 1)$ *and the intercept of the demand is sufficiently large* ($a > 5(c+I_g)$)*, the merit order rule lead to an equilibrium which benefits both the renewable producer and the consumers if the expected value of capacity availability is larger than a certain threshold, i.e. if* $x^* > \hat{x}$*.*

PROOF. Given the monotonicity of demand, E^{IC} is preferred by consumers with respect to E^{LC} if it leads to a lower price:

$$p^{IC} = \frac{x^*(a+c+I_g)+2I_s}{4x^*} < \frac{a+c+I_g}{3} = p^{LC} \tag{23}$$

This condition is verified when:

$$a > 5(c+I_g) \tag{24a}$$

$$x^* > \hat{x} \tag{24b}$$

[15] We exclude from this analysis the strictly dominated strategy of investing in Small capacity.

The second inequality may hold only when the investment cost in the renewable technology is relatively small:[16]

$$\frac{6I_s}{a+c+I_g} = \hat{x} < 1 \tag{25}$$

Indeed if $\hat{x} > 1$, the condition 24b would imply an $x^* > 1$ which is impossible by assumption.■

If the investment cost in the PV technology is relatively large, consumers and PV producer interests cannot be reconciled because the former will always prefer a Large PV capacity, while the latter will always invest in an Intermediate capacity. In this case, consumers' loss is inversely related to the expected value of capacity availability: the larger the x^* is, the smaller the difference between consumer surplus in equilibria E^{IC} and E^{LC}. More interestingly, if the investment cost in the PV technology is relatively small, consumer and PV producer interests may be aligned (see Figure 3). It is worth noting that when parameters values are such that the PV generator is indifferent between investing in an Intermediate or Large capacity, the consumers are still better-off if the producer choose the second strategy since it will lead to lower prices and a larger quantity.

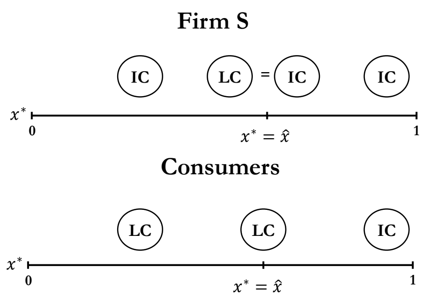


Figure 3: Preferences over strategies,
Relatively small PV investment cost

In order to align consumers and S interest when the investment cost in PV technology is relatively small, the expected value of capacity availability must be larger than $\hat{x}$. In this case, there seems to be some room for welfare improving public interventions.

[16]The inequality must be strict in this case for condition 24b to hold.

Corollary 3. *When the investment cost in the PV technology is relatively small ($\hat{x} \leq 1$), a public intervention which further reduces this cost increases the likelihood of a market outcome in which both the PV producer and the consumers are better-off.*

If on the one hand, the expected value of capacity availability depends on the technology and cannot be exogenously modified, on the other hand $\hat{x}$ is increasing in the investment cost of PV technology: a policy which reduces such cost increases the likelihood of a market outcome in which the interests of the PV producer and the consumers converge.[17] Let us illustrate this result with a simple numerical example. Suppose that $a = 200$, $b = 1$, $I_g = 20$, $c = 1$, $I_s = 36$. Investing in an Intermediate capacity is the strictly dominant strategy for S for any value of x^*, except when $x^* = \hat{x} = 0.97$ in which case investing in Large capacity leads to an identical profit. Consumers are better-off when S invest in an Intermediate capacity only if $x^* > 0.97$, whereas for $x^* \leq 0.97$ they will always prefer a Large PV capacity. This is a very restrictive condition given that 1 is the upper bound of x^*. Now suppose that the cost of investing in PV capacity decreases to 22 €. In this case S still prefers to invest in an Intermediate capacity for any value of x^* (and it is indifferent with respect to Large capacity if $x^* = \hat{x} = 0.59$), while it suffices to have $x^* > 0.59$ to align PV generator and consumers interest. A smaller PV investment cost increases therefore the range of expected capacity availability values for which consumer are better-off with S choosing an Intermediate capacity.

4. Expected ex-post profits

In the previous section, the optimal behaviour of firm S has been calculated by comparing the so-called ex-ante profits of each strategy, i.e. the pay-offs obtained on the basis of the expected value of capacity availability, x^*. However once the capacity has been installed, the PV production depends on the actual value of x. The objective of this section is to verify that the optimal ex-ante strategy for S remains ex-post optimal. In order to do so we analyze what we call the expected

[17] A public intervention may generate a market distortion; therefore the specific instrument that may be used must be carefully chosen.

ex-post pay-offs of firm S, defined as the expected value of profits obtained when the firm invests in capacities k^{IC} or k^{LC} of previous section[18] and it produces according to the real value of x. We firstly use a generic probability density function, $P(x)$, defined for $x \in [0,1]$, for which the following condition must hold:

$$\mathbb{E}[f] = \int_0^1 f(x)P(x)dx \tag{26}$$

The expected value of ex-post profit is defined:

$$\mathbb{E}[\Pi^{LC,IC}] = \int_0^1 \Pi^{LC,IC}(x)P(x)dx \tag{27}$$

where:

$$\Pi^{LC,IC} = (a - bq_g^{LC,IC} - bxk^{LC,IC})xk^{LC,IC} - I_s k^{LC,IC} \tag{28}$$

G always produces the lower quantity between its installed capacity and its optimal production given the electricity supplied by S:

$$q_g^{LC,IC} = \frac{a - b\max(x, x^*)k_s^{LC,IC} - c - I_g}{2b} \tag{29}$$

The results of the calculations are reported in the following proposition.

Proposition 3. *For the Intermediate capacity strategy to be ex-post superior to the Large capacity strategy, i.e.* $\mathbb{E}[\Pi^{IC}] > \mathbb{E}[\Pi^{LC}]$*, the following condition must hold:*

$$\frac{1 - 6t + 5t^2}{4t^2}(M - 2Var[x]) > \hat{x}^2 t(t-1) \tag{30}$$

where:

$$\mathbb{E}[x] = x^* \tag{31a}$$

$$Var[x] = \mathbb{E}[x^2] - \mathbb{E}[x]^2 \tag{31b}$$

$$M = \int_0^1 x\max(x, x^*)P(x)dx \tag{31c}$$

$$t = \frac{x^*}{\hat{x}} \tag{31d}$$

[18] We have dropped the subscript s for expositional convenience.

PROOF. See Appendix A.

To get some insights on the ex-post ranking of strategies we use a uniform distribution function defined as follows:

$$P(x) = \begin{cases} \frac{1}{2\varepsilon} & \text{for } x^* - \varepsilon \leq x \leq x^* + \varepsilon \\ \\ 0 & \text{otherwise} \end{cases} \tag{32}$$

With this distribution we have:

$$M = \frac{\varepsilon^2}{6} + \frac{x\varepsilon}{4} + x^2 \tag{33a}$$

$$\mathrm{Var}[x] = \frac{\varepsilon^2}{3} \tag{33b}$$

We can rewrite therefore the inequality 30 so as to obtain:

$$\frac{1}{16t^2}(5t-1)(4\hat{x}^2t^2 + \hat{x}t\varepsilon - 2\varepsilon^2) > \hat{x}^2 t \tag{34}$$

We have performed some simulations using different values of $\hat{x}$. When the investment cost in the PV technology is relatively large ($\hat{x} > 1$), the PV generator never chooses to invest in a Large capacity neither ex-ante nor ex-post. Figures 4 to 7 show simulations results when the investment cost in the PV technology is instead relatively small, i.e. $\hat{x} \leq 1$. The red areas represent the values of parameters for which investing an in Intermediate capacity is the ex-post preferred strategy, whereas purple areas indicate the values for which investing in a Large capacity becomes ex-post preferred. We consider that the forecasting of the expected value of capacity availability is subject to limited errors, i.e. $\varepsilon = 0.1$.

We have seen that when the investment cost in the PV technology is relatively small, the PV producer may be ex-ante indifferent between an Intermediate and a Large capacity at a very strict condition ($x^* = \hat{x}$). The analysis of expected ex-post profits reveals that the renewable producer may strictly ex-post prefer to invest in a Large capacity for a certain range of expected capacity availability values. Consider the following numerical example. When $\hat{x} = 0.75$ (see Figure 7) investing in a Large capacity is ex-ante equal to investing in an Intermediate capacity if and only if $x^* = 0.75$. The ex-post analysis suggests that for $0.675 < x^* < 0.75$ investing in a Large capacity becomes ex-post the optimal strategy.[19] This result is summarized in the following corollary.

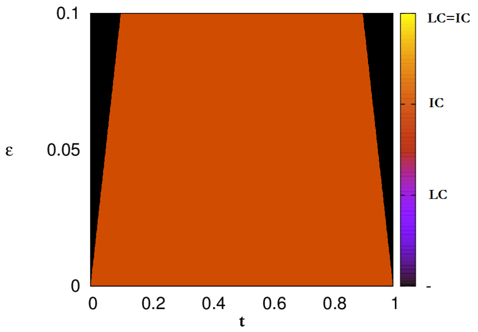


Figure 4: $\hat{x} = 1$

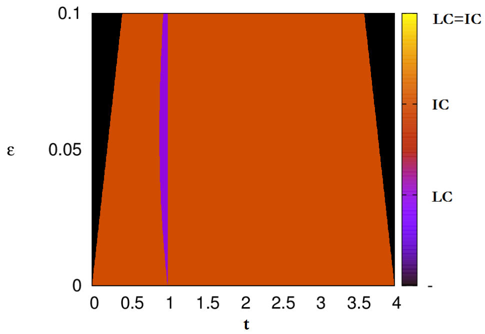


Figure 5: $\hat{x} = 0.25$

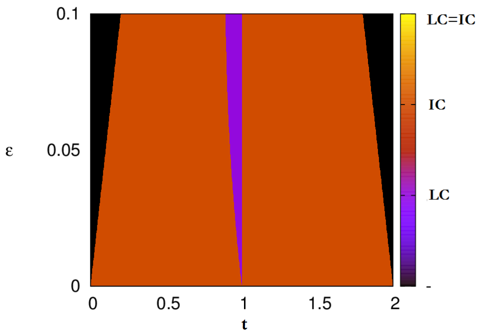


Figure 6: $\hat{x} = 0.5$

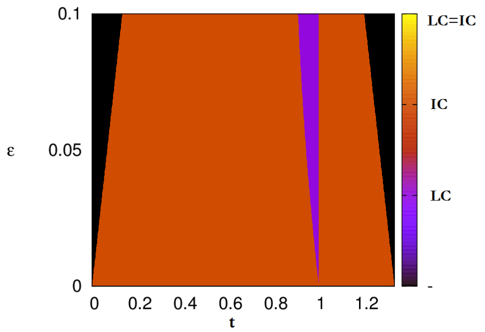


Figure 7: $\hat{x} = 0.75$

Corollary 4. *When the investment cost in the PV technology is relatively small, the renewable producer may prefer to invest in a Large capacity, even for small forecasting errors, when the production varies according to the true value of capacity availability. The imperfect predictability of production may therefore determine larger strategic PV investments with respect to what suggested by the ex-ante analysis alone.*

5. Three stage game

In this section we study the effect on equilibrium outcomes following a change in competition rules in post-investment stage. We adopt the dominant firm - competitive fringe setting developed

[19] $x^* = t \cdot \hat{x} = 0.9 \cdot 0.75 = 0.675$

by Carlton and Perloff (1994) to model competition in production where the traditional producer represents the dominant firm and the renewable generator behaves like a competitive fringe. This extension aims at accounting for price taking behavior of renewable producers when their bids are individually submitted in spot electricity markets. In our stylized model with two technologies, 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.

When not explicitly modified, all previous assumptions and notations hold. In this model, 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, $I_s k_s$.[20] 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. The structure of the game is the following:

1. in the first stage the firm S chooses its capacity investment, k_s: the investment is irreversible in the sense that capacity already installed cannot be dismissed in the following stages;

2. 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;[21]

3. In the third stage, S chooses its production possibly increasing its capacity prior to compete for production.

The game is solved by backward induction. The following proposition summarizes the possible strategies that the renewable producer can implement in the first stage of the game and characterizes the corresponding game equilibrium.

Proposition 4. *In the first stage of the game S may choose to invest in a Very Small (VSC), Small (SC), Large (LC), Very Large (VLC) or Intermediate (IC) capacity. According to the capacity*

[20] The convex production cost function may be justified by the fact that once the better sites for renewable installation are occupied, less accessible sites must be developed with increasing cost.

[21] Again this stage can be viewed as the one in which G adjusts its production if the capacity has been already installed.

installed by S in the first stage, the game has five equilibria. The equilibria, which are detailed in the Appendix B, are sketched in Figures 8 to 12.

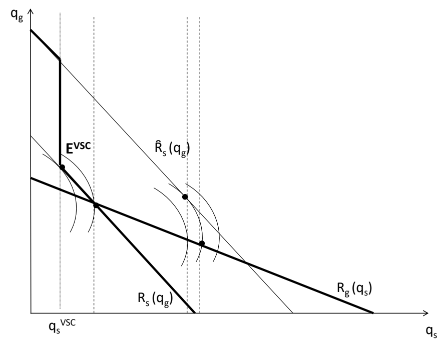


Figure 8: Equilibrium E^{VSC}

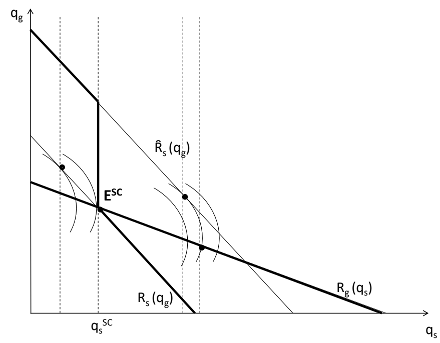


Figure 9: Equilibrium E^{SC}

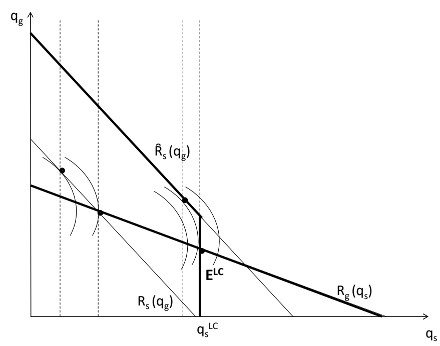


Figure 10: Equilibrium E^{LC}

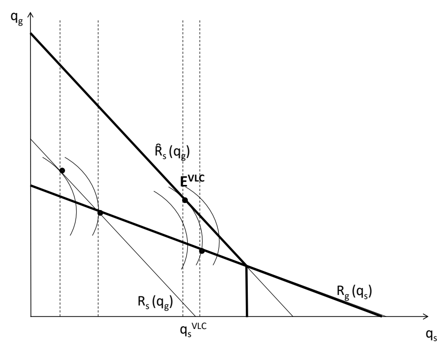


Figure 11: Equilibrium E^{VLC}

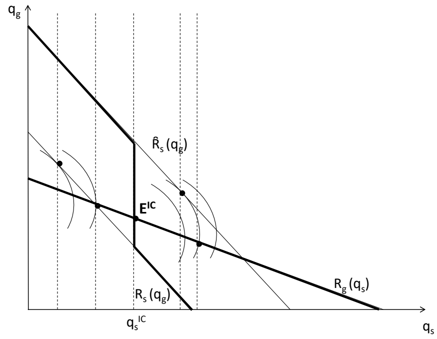


Figure 12: Equilibrium E^{IC}

Contrary to the two stage game, the ranking of strategies here depends on the values of parameters. However, some strictly dominated strategies can be immediately eliminated. By looking at the graphics, we observe that when the renewable generator prefers to postpone investments and hence presents in the last stage of the game the inner reaction function, between point E^{VSC} in Figure 8 and point E^{SC} in figure 9, it surely prefers the latter equilibrium. Hence the strategy leading to equilibrium E^{VSC} is always dominated by the strategy corresponding to equilibrium E^{SC}. 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 E^{LC} in Figure 10 and equilibrium E^{VLC} in Figure 11 it will always prefer equilibrium at point E^{LC} . Therefore, although the PV producer is the follower in the production game, it can eliminate strictly dominated strategies leading to points such as E^{VSC} and E^{VLC} 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 E^{SC} -E^{LC} as it does in the two stage game. The strategic incentives depending on merit order rule still hold. The only difference here is in that the segment E^{SC} -E^{LC} is shorter than in the two stage game, which constraints the set of possible capacity choices.

For illustrative purpose we have calculated the payoffs of each strategy as a function of x^*, using the following parameters values: $c_s = 0.1$, $b = 1$, $I_s = 50$, $F_s = 80$, $c_g = 20$, $I_g = 46.3$, $a = 500$. The value of c_s is sufficiently small to reflect the fact that the production cost of renewable power grows at a slow rate, whereas the other parameters for investment and production costs are chosen to be reasonably closed to the reality (see footnote 9). The results are shown in figure13.

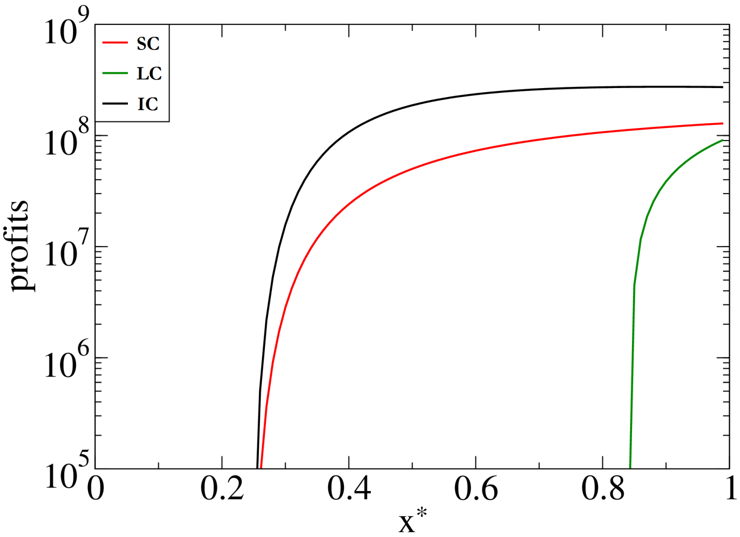


Figure 13: Profit functions

We remark that investing in the Intermediate capacity (IC) provides the PV firm with the largest profit for any value of the expected capacity availability. For a large range of x^* the strategy of investing in the Small capcity (SC) is the second preferred one while we may observe that when x^* is closed to its upper bound investing in a Small capacity (SC) or in a Large capacity (LC) leads to very similar profit levels.

6. Policy implications and conclusions

Overtime a number of policy interventions contributed to reshape electricity industries worldwide. In European Union, the Third Energy Package (2009) has completed the process of liberalization of generation and retail activities which have been fully opened up to competition; spot electricity markets have also been created. One of the reform's goals was to boost sector's efficiency by increasing capacity adequacy and achieving technology mix optimality. Alongside with liberalization, European Union has approved in 2009 the Climate and Energy Package which establishes, among others, compulsory targets for enhancing investments in renewable technologies for power generation. 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.

In this article we have proposed a stylized theoretical model for the analysis of competition between a traditional and a renewable power generator in the context of spot electricity markets. The interest of defining an *ad hoc* model stems from the fact that existing models of imperfect competition analyzing generators' behavior in liberalized electricity markets do not take into account two main features of production and trade of renewable power. First, the production from renewable sources, in particular wind and sun, is characterized by uncertainty due to the partial unpredictability of weather conditions. Second, merit order rule guarantees that the renewable power is always the first to be brought online to meet the demand given that the production from renewable sources has zero or negligible variable costs.[22] The large penetration of renewable generation experienced by European Countries has redefined the rules of the game in decentralized spot market: on the one hand merit order rule has allowed renewable producers to enjoy a sort of first mover advantage and the renewable supply has partly crowded out the production from mid-merit power plants; on the other hand the increasing reliance on renewable generation has intensified the needs for traditional, immediately available, back-up capacity to overcome the intermittency and to guarantee inflows and outflows balance.

Our model intends to investigate how market mechanisms and technology attributes intervene on renewable producer behavior and in particular on its capacity choices. The analysis has revealed that the capacity size of renewable producer tends to be larger than a model of imperfect quantity competition between traditional power generators may suggest. Indeed merit order rule creates an incentive for the renewable producer to invest in a large generation capacity in order to modify competition in production to its own advantage. This strategic incentive exists regardless to the market power of renewable producer: even when it behaves as a competitive fringe in the

[22] All multi-unit auction (for treasury bills, emission allowances, radio spectrum, etc.) accept offers according to a merit order: the lower offer prices are taken first and higher offers are subsequently accepted until total demand is met. Nevertheless, in the wholesale electricity markets renewable generation benefits from a technological advantage with respect to its competitors which is related to the negligible level of short run marginal cost.

production game it may be able to modify short run competition through the choice of investments. It will then try to have an available capacity as large as possible to increase its production.

The analysis reveals also that consumers may benefit from the expansive capacity choices of renewable producer depending on the level of the investment cost in the renewable technology and on the expected value of renewable capacity availability. In this case, a public intervention which further reduces the investment cost in the renewable technology may be desirable as it increases consumer surplus when the renewable producer plays its optimal strategy. We have also demonstrated, in line with the classical theory of entry deterrence, that if the forecast of the expected value of renewable capacity availability is subject to some errors and the investment cost is relatively small, merit order pushes the renewable producer to invest in an even larger capacity further reducing its rival production.

The results of this analysis have important policy implications. Renewable generators may be biased by spot market design to increase their optimal size toward medium/large power plants. The growth of installed capacity may not correspond in this case to an increase in system reliability, on the contrary. A larger renewable capacity pushes the traditional producer to cut on their future investments due to a reduced profitability. The negative effect of merit order rule on traditional production must be counterbalanced in order to restore the correct investment incentives, a recent proposal being the creation of capacity markets alongside “energy-only” markets.

The adoption of merit order rule developed in peak-load pricing theory (see Crew et al., 1995) has ensured up to now the efficiency of electricity spot market; however its benefits might be questioned in consideration of the evolution of market structure and technological features of power generation. To this end, additional research seems to be necessary to understand how producers behaviors have changed and what are, in the present context, the consequences on welfare of different market rules.

Acknowledgement

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Appendix A - Ex-post analysis calculations

PROOF. We obtain the values of ex-post profits by substituting in equation 28 the optimal values of k^{LC} and k^{IC} in Proposition 1 and the optimal quantity of firm G (equation 29):

$$\begin{aligned}\Pi^{LC} = \left(a - b\left(\frac{a - b\max(x,x^*)k^{LC} - c - I_g}{2b}\right)\right)x\left(\frac{a+c+I_g}{3bx^*}\right) - \\ bx^2\left(\frac{a+c+I_g}{3bx^*}\right)^2 - I_s\left(\frac{a+c+I_g}{3bx^*}\right)\end{aligned} \tag{35}$$

$$\begin{aligned}\Pi^{IC} = \left(a - b\left(\frac{a - b\max(x,x^*)k^{IC} - c - I_g}{2b}\right)\right)x\left(\frac{x^*(a+c+I_g) - 2I_s}{2bx^{*2}}\right) - \\ bx^2\left(\frac{x^*(a+c+I_g) - 2I_s}{2bx^{*2}}\right)^2 - I_s\left(\frac{x^*(a+c+I_g) - 2I_s}{2bx^{*2}}\right)\end{aligned} \tag{36}$$

Calling $A = a + c + I_g$, the two expressions may be simplified as:

$$\Pi^{LC} = -\frac{A}{3bx^*}\left(I_s + \frac{2Ax^2 - 3Axx^* - Ax\max(x,x^*)}{6x^*}\right) \tag{37a}$$

$$\Pi^{IC} = (Ax^* - 2I_s)\frac{2(x-x^*)(Axx^* - 2I_s(x+x^*)) + x(2I_s - Ax^*)\max(x,x^*)}{8bx^{*4}} \tag{37b}$$

To calculate their expected values, 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:

$$\mathbb{E}[f] = \int_0^1 f(x)P(x)dx \tag{38}$$

Expected ex-post profits are therefore:

$$\mathbb{E}[\Pi^{LC,IC}] = \int_0^1 \Pi^{LC,IC}(x)P(x)dx \tag{39}$$

For strategy LC we have:

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

where:

$$M = \int_0^1 x\max(x,x^*)P(x)dx \tag{40}$$

Simplifying:

$$\mathbb{E}[\Pi^{LC}] = -\frac{AI_s}{3bx^*} - \frac{A^2\mathbb{E}[x^2]}{9bx^{*2}} + \frac{A^2}{6b} + \frac{A^2 M}{18bx^{*2}} \tag{41}$$

For strategy IC, let us firstly rewrite the ex-post profits as:

$$\Pi^{IC} = \frac{I_s}{2bx^{*2}}(2I_s - Ax^*) - \frac{(2I_s - Ax^*)^2}{4bx^{*4}}x^2 + \frac{(2I_s - Ax^*)[(2I_s - Ax^*)\max(x, x^*) - 2Ax^{*2}]}{8bx^{*4}}x =$$

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

where $B = 2I_s - Ax^*$.

The expected ex-post profits are:

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

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

Using again the definition of M we obtain:

$$\mathbb{E}[\Pi^{IC}] = \frac{I_s B}{2bx^{*2}} - \frac{AB}{4bx^*} - \frac{B^2}{4bx^{*4}}\mathbb{E}[x^2] + \frac{MB^2}{8bx^{*4}} \tag{42}$$

Recalling that $\mathbb{E}[x] = x^*$, we may rewrite the expected profits of strategies LC and IC using the definition of variance of a random variable, $\mathrm{Var}[x] = \mathbb{E}[x^2] - \mathbb{E}[x]^2$:

$$\mathbb{E}[\Pi^{LC}] = \frac{A^2}{18b} - \frac{AI_s}{3bx^*} + \frac{A^2}{18bx^{*2}}(M - 2\mathrm{Var}[x]) \tag{43a}$$

$$\mathbb{E}[\Pi^{IC}] = \frac{2I_s B - B^2}{4bx^{*2}} - \frac{AB}{4bx^*} + \frac{B^2}{8bx^{*4}}(M - 2\mathrm{Var}[x]) \tag{43b}$$

The condition $\mathbb{E}[\Pi^{LC}] < \mathbb{E}[\Pi^{IC}]$ is therefore equivalent to:

$$\frac{A^2}{18} - \frac{AI_s}{3x^*} + \frac{A^2}{18x^{*2}}(M - 2\mathrm{Var}[x]) < \frac{B^2}{8x^{*4}}(M - 2\mathrm{Var}[x]) \tag{44}$$

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

$$\frac{A^2}{18} - \frac{AI}{18x^*} + \frac{A^2}{18x^{*2}}(M - 2\mathrm{Var}[x]) < \frac{(\frac{I}{3} - Ax^*)^2}{8x^{*4}}(M - 2\mathrm{Var}[x]) \tag{45}$$

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

$$\frac{A^2 x^{*2}}{I^2} - \frac{Ax^*}{I} + \frac{A^2}{I^2}(M - 2\mathrm{Var}[x]) < \frac{(1 - 3x^*\frac{A}{I})^2}{4x^{*2}}(M - 2\mathrm{Var}[x]) \tag{46}$$

We have already defined $\hat{x} = \frac{I}{A} = \frac{6I_s}{a+c+I_g}$. We use $\hat{x}$ in order to reduce the previous inequality to:

$$\frac{x^{*2}}{\hat{x}^2} - \frac{x^*}{\hat{x}} + \frac{1}{\hat{x}^2}(M - 2\mathrm{Var}[x]) < \frac{(1-\frac{3x^*}{\hat{x}})^2}{4x^{*2}}(M - 2\mathrm{Var}[x]) \tag{47}$$

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

$$t(t-1) < \left(t^2 - \frac{(1-3t)^2}{4}\right)\frac{2\mathrm{Var}[x] - M}{\hat{x}^2} \tag{48}$$

By further simplification we obtain equation 30:

$$\frac{1-6t+5t^2}{4t^2}(M - 2\mathrm{Var}[x]) > \hat{x}^2 t(t-1) \tag{49}$$

■

Appendix B - Three stage game calculations

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:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[MC(q_s, k_s)] \quad \text{where} \tag{50a}$$

$$MC(q_s, k_s) = \begin{cases} F_s + c_s q_s & \text{if } q_s \leq x k_s \\ \frac{I_s}{x} + F_s + c_s q_s & otherwise \end{cases} \tag{50b}$$

S reaction function is a kinked curve whose shape depends on the investment decisions that have been taken in previous stages of the game. Just like in the two stage game, it is possible to calculate the thresholds of q_g that make the PV producer switching from a reaction curve to another, given that the expected market price is a decreasing function of the quantity of electricity provided by firm G.[23] 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, $\forall q_g > q_g^h$:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[F_s + c_s q_s] \tag{51a}$$

$$\tilde{R}_s(q_g) = q_s = \frac{a - bq_g - F_s}{c_s + b} \tag{51b}$$

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

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[\frac{I_s}{x} + F_s + c_s q_s] \tag{52a}$$

$$R_s(q_g) = q_s = \frac{x^*(a - bq_g - F_s) - I_s}{(c_s + b)x^*} \tag{52b}$$

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

$$\bar{R}_s = q_s = x^* k_s \tag{53}$$

[23]Note that if q_g is very large, i.e. $q_g > \frac{a-F_s}{b}$, then $q_s = 0$.

Very Small capacity (VSC) and Small capacity (SC)

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:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}\left[\frac{I_s}{x} + F_s + c_s q_s\right] \tag{54}$$

The optimal q_s is calculated as a function of q_g:

$$q_s = \frac{x^*(a - bq_g - F_s) - I_s}{(c_s + b)x^*} \tag{55}$$

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:

$$\begin{aligned} \underset{q_g, k_g}{\text{Max}} \quad \mathbb{E}[\Pi_g] = \mathbb{E}[p^d(q_g)q_g - cq_g - I_g k_g] \quad & \text{subject to} \\ q_g \leq k_g & \end{aligned} \tag{56}$$

where:

$$p^d = \frac{ac_s x^* + b[I_s + (F_s - c_s q_g)x^*]}{(c_s + b)x^*} \tag{57}$$

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

$$k_g^{VSC} = q_g^{VSC} = \frac{c_s(a - c_g - I_g)x^* + b[I_s + (F_s - c_g - I_g)x^*]}{2bc_s x^*} \tag{58}$$

By substituting G's optimal quantity in equations 55 and 57, we obtain S's optimal quantity and equilibrium price from which we can calculate firms' profits:

$$q_s^{VSC} = \frac{c_s(Ax^* - 2I_s) - b(Bx^* + I_s)}{2c_s(c_s + b)x^*} \tag{59a}$$

$$p^{VSC} = \frac{c_s C x^* + b(I_s + D x^*)]}{2(c_s + b)x^*} \tag{59b}$$

$$\Pi_s^{VSC} = \frac{[c_s(Ax^* - 2I_s) - b(Bx^* + I_s)]^2}{8c_s(c_s + b)^2 x^{*2}} \tag{59c}$$

$$\Pi_g^{VSC} = \frac{[c_s E x^* + b(Bx^* + I_s)]^2}{4bc_s(c_s + b)x^{*2}} \tag{59d}$$

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 E^{VSC} in Figure 8 and arises in the third stage of the game if in the earlier stage firm S has installed:

$$k_s^{VSC} \leqslant \frac{c_s(Ax^* - 2I_s) + b(Bx^* - I_s)}{2c_s(c_s + b)x^{*2}} \tag{61}$$

When in the first stage of the game S has invested in a capacity which is larger than k_s^{VSC} 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 E^{VSC} is unattainable. Therefore to find its optimal quantity and capacity G maximizes its profits over the residual demand as in 56: each time the residual demand will be the difference between the market demand and the quantity of electricity provided by S, $q_s = x^* k_s$. This equilibrium occurs in a point on the right portion of the segment $E^{VSC} - E^{SC}$ in Figures 8 and 9 (excluding point E^{VSC}).[24]

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

If in the earlier stage S has installed the Cournot capacity the tangency point occurs in E^{SC} (Figure 9) and the optimal response of firm G is to produce exactly Cournot. In this case, the equilibrium outcome is:

$$q_s^{SC} = \frac{Ax^* - 2I_s}{(2c_s + b)x^*} \tag{62a}$$

$$q_g^{SC} = \frac{c_s E x^* + b(Bx^* + I_s)}{b(2c_s + b)x^*} \tag{62b}$$

$$p^{SC} = \frac{c_s C x^* + b(I_s + F_s x^*)}{(2c_s + b)x^*} \tag{62c}$$

$$\Pi_s^{SC} = \frac{c_s(Ax^* - 2I_s)^2}{2(2c_s + b)^2 x^{*2}} \tag{62d}$$

$$\Pi_g^{SC} = \frac{[c_s E x^* + b(Bx^* + I_s)]^2}{b(2c_s + b)^2 x^{*2}} \tag{62e}$$

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

$$k_s^{SC} = \frac{Ax^* - 2I_s}{(2c_s + b)x^{*2}} \tag{63}$$

Large capacity (LC) and Very Large capacity (VLC)

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 alone. In this case, firm S chooses its optimal quantity as the solution to the equation:

$$\mathbb{E}[a - bq_g - bq_s] = \mathbb{E}[F_s + c_s q_s] \tag{64}$$

which gives the quantity q_s as a function of q_g:

$$q_s = \frac{a - bq_g - F_s}{c_s + b} \tag{65}$$

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 56 but in this case the residual demand is equal to:

$$p^d = \frac{bF_s + c_s(a - bq_g)}{c_s + b} \tag{66}$$

At the optimum G installs and produces:

$$k_g^{VLC} = q_g^{VLC} = \frac{c_s E + bB}{2c_s b} \tag{67}$$

Again, by substituting G's optimal quantity in equations 65 and 66, we obtain S's optimal quantity, equilibrium price and profits:

$$q_s^{VLC} = \frac{c_s A - bB}{2c_s(c_s + b)} \tag{68a}$$

$$p^{VLC} = \frac{c_s C + bD}{2(c_s + b)} \tag{68b}$$

$$\Pi_s^{VLC} = \frac{[c_s A - bB]^2}{8c_s(c_s + b)^2} \tag{68c}$$

$$\Pi_g^{VLC} = \frac{[c_s E + bB]^2}{4c_s b(c_s + b)} \tag{68d}$$

This equilibrium is represented as point E^{VLC} in Figure 11. By constructing the isoprofit curve of G passing through the equilibrium point E^{VLC} we see that it meets firm G reaction function in point E^{LC} (Figure 10). The coordinates of such point are:

$$q_s^{LC} = \frac{E\sqrt{c_s(c_s + b)} - c_s E - bB}{b\sqrt{c_s(c_s + b)}} \tag{69a}$$

$$q_g^{LC} = \frac{c_s E + bB}{2b\sqrt{c_s(c_s + b)}} \tag{69b}$$

This point ensures to G the same profits of equilibrium E^{VLC}. Through the demand function we can calculate the market price and profits of S:

$$p^{LC} = \frac{bB + c_s E + 2\sqrt{c_s(c_s + b)}(c_g + I_g)}{2\sqrt{c_s(c_s + b)}} \tag{70}$$

$$\Pi_s^{LC} = \frac{\left\{\left[c_s - \sqrt{c_s(c_s + b)}\right]E + bB\right\}\left\{\left[c_s^2 - c_s\sqrt{c_s(c_s + b)}\right]E + b^2B + b\left[c_s H - 2\sqrt{c_s(c_s + b)}B\right]\right\}}{2b^2 c_s(c_s + b)} \tag{71}$$

where:

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

Equilibrium E^{VLC} is preferred by CCGT producer when in the first stage S has installed:

$$k_s > \frac{q_s^{LC}}{x^*} = \frac{E\sqrt{c_s(c_s + b)} - c_s E + bB}{x^* b\sqrt{c_s(c_s + b)}} \tag{72}$$

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

Intermediate capacity (IC)

When in the third stage of the game firm S produces at available capacity, firm G is constrained to behave as a Stackelberg follower, which means that the first mover advantage in production of firm G is completely lost. Let us call this equilibrium E^{IC}. Gas producer's reaction function is the same as the one calculated in the two stage game:

$$R_g(k_s) = q_g^E = \frac{a - bx^* k_s - c_g - I_g}{2b} \tag{73}$$

Equilibrium price and profits in implicit form are:

$$p^{IC} = \frac{a - bx^* k_s + c_g + I_g}{2} \tag{74a}$$

$$\Pi_s^{IC} = \left(\frac{a - bx^* k_s + c_g + I_g}{2} - F_s - \frac{c_s x^* k_s}{2} \right) x^* k_s \tag{74b}$$

$$\Pi_g^{IC} = \frac{(a - bx^* k_s - c_g - I_g)^2}{4b} \tag{74c}$$

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

$$\underset{k_s}{\text{Max}} \quad \mathbb{E}[\Pi_s] = \mathbb{E}\left[p(xk_s, q_g) xk_s - \left(\frac{I_s}{x} + F_s + \frac{c_s x k_s}{2} \right) xk_s \right] \tag{75}$$

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

$$k_s^E = \frac{Ax^* - 2I_s}{2(c_s + b)x^{*2}} \tag{76a}$$

$$q_s^E = \frac{x^* A - 2I_s}{2(c_s + b)x^*} \tag{76b}$$

$$q_g^E = \frac{x^* \left\{ b[a - 3(c_g + I_g) + 2F_s] + 2c_s E \right\} + 2bI_s}{4b(c_s + b)x^*} \tag{76c}$$

$$p^E = \frac{x^* [b(a + c_g + I_g + 2F_s) + 2c_s C] + 2bI_s}{4(c_s + b)x^*} \tag{76d}$$

$$\Pi_s^E = \frac{[Ax^* - 2I_s]^2}{8(c_s + b)x^{*2}} \tag{76e}$$

$$\Pi_g^E = \frac{\left\{ x^* \left\{ b[a - 3(c_g + I_g) + 2F_s] + 2c_s E \right\} + 2bI_s \right\}^2}{16b(c_s + b)^2 x^{*2}} \tag{76f}$$