Conventional Power Plants in Liberalized Electricity Markets with Renewable Entry

Gerard Llobet and Jorge Padilla***

ABSTRACT

This paper examines the optimal capacity choices of conventional power generators after the introduction of renewable production. We start with a basic and generally accepted model of the liberalized wholesale electricity market in which firms have insufficient incentives to invest and we illustrate how the entry of renewable generation tends to aggravate that problem. We show that the incentives to invest in firm capacity (e.g. conventional thermal plants) may be restored by means of a capacity auction mechanism. That mechanism is vulnerable and, hence, may prove ineffective unless governments can credibly commit not to sponsor the entry of new capacity outside the auction mechanism. We explain that such commitment may be particularly difficult in the current political context where energy policy is conditioned by environmental and industrial-policy goals. We finally propose a way to enhance the credibility of capacity auctions by committing to optimally retire idle (conventional) power plants in response to entry outside the auction.

Keywords: Conventional Generation, Renewable Energy, Security of Supply, Missing-Money Problem, Environmental Goals, Capacity Payments

https://doi.org/10.5547/01956574.39.3.gllo

1. INTRODUCTION

The increasing penetration of renewable energy has had a profound impact on the economic performance and financial health of conventional power producers. These renewable plants have caused average and peak wholesale electricity prices to decline and triggered a reduction in the utilization of conventional thermal plants. At the same time, the volatility of renewable production has made conventional power plants even more critical to ensure generation adequacy and security of supply. This situation has been explicitly recognized, for example, by the European Commission in its December 2016 final report on capacity mechanisms (European Commission, 2016):

> Electricity generation from renewable energy sources is growing rapidly. This has resulted in lower wholesale electricity prices, but has also reduced the use of conventional generation technologies, such as coal and gas, because renewable energy generally has lower running costs. Declining demand, lower prices and lower utilisation rates have all reduced the profitability of conventional electricity generation. At the same time, flexible conventional technologies continue to play a very important role: the growing share of renewable energy sources like wind and solar energy, the output of which varies with weather conditions and from daytime to night time, requires flexible energy systems,

* Corresponding author. CEMFI. Send correspondence to CEMFI, Casado del Alisal, 5, Madrid 28014, Spain. E-mail: llobet@cemfi.es.

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including reliable back-up capacity, that can take the form of conventional generation, demand-response or storage, to ensure security of supply at all times.

The two conflicting effects of the integration of renewable energy in electricity markets has created a challenge for market regulators, that have responded by establishing a variety of capacity remuneration schemes.[1] These mechanisms aim to provide back-up production by discouraging firms from mothballing or decommissioning existing efficient plants and fostering investment in cleaner conventional power plants that replace older and more polluting ones. In practice, however, they have proved difficult to implement due to the adoption of increasingly ambitious environmental goals, which require adding generation capacity over and above the levels originally planned.

How capacity payments should adapt to the entry of renewable capacity that is *exogenous* to market goals is part of the current debate in many countries and it has led to different solutions. The UK has conducted capacity auctions in 2015 and 2016 to foster the entry of firm capacity to compensate the earlier limited investment in a context of growing demand and aging conventional plants that are expected to retire in the near future. In the US, the tensions between state environmental goals and regional market regulators have called for a revision of their capacity mechanisms. The New England system operator has recently proposed a new two-stage capacity mechanism to efficiently integrate renewable power in capacity markets over time while providing the right price signals (ISONE, 2017). Germany is in the process of creating a capacity reserve scheme. The province of Alberta in Canada is introducing a capacity mechanism to its previously energy-only market.

These initiatives aim to improve the credibility of capacity mechanisms and stand in contrast with decisions adopted in countries like Spain where, in a context of declining prices due to the impact of a surge of renewable capacity, the government has sharply reduced capacity payments.

These contrasting policies reflect the considerable differences of opinion among policy makers and market experts as to the consequences of the introduction of renewable energy into liberalized wholesale electricity markets. In this paper we seek to clarify in simple terms the economic impact of renewable generation on electricity markets, an issue which is often discussed from an ideological viewpoint. In particular, we discuss how to foster investment in firm capacity in power markets with significant renewable production by means of capacity auctions when renewable power goals change over time. We explain that the credibility and, hence, the efficiency of such auctions will be undermined by interventions leading to increases in renewable capacity when they occur after the capacity auction has been closed and the investment committed at the auction has been sunk. We also propose a mechanism that redresses the distortions created and discuss its limitations.

We start with a simple economic model that, based on generally accepted assumptions, encompasses the main reasons proposed in the literature to introduce capacity payments. This model illustrates how the entry of renewable generation affects the functioning of power markets, as it reduces the market price, increases its volatility and reduces the hours of operation of conventional power producers. In the long run, the decrease in market prices and running hours caused by the entry of renewable plants slashes the profitability of conventional plants. This may lead to the exit of some of them (when that is feasible from a regulatory viewpoint) and to the reduction in the incentives to invest in conventional generation in the future, thus giving raise to security of supply concerns. In the short run, however, our model indicates that conventional power plants and renewable ones are very likely to have complementary features, given the intrinsic volatility of the

1. Under this term we denote a wide variety of implementations of remuneration mechanisms. In some cases, payments are directly determined by the government, whereas in some countries they are obtained as the result of capacity auctions.

production of the latter. The reason is that the peak production that renewable power sources may attain is likely to be useful in limited circumstances, whereas the disruption generated by its unavailability is more likely to occur. As a result, conventional power sources become more critical to the smooth functioning of the market when volatile renewable plants are introduced. Our findings on short-run complementarity are consistent with empirical evidence provided in studies like Shrimali and Kniefel (2011).[2]

Our model focuses on the two main reasons that have been emphasized in the literature to explain why energy-only markets (i.e. markets where only the energy produced is remunerated) often fail to provide adequate signals for capacity investment: the establishment of price caps and the presence of externalities related, for example, to blackouts.

As in this paper, price caps set by regulators have received the most attention. When capacity is tight energy-only markets generate price spikes that contribute to recover the fixed costs of generators. To reach optimal investment levels, these scarcity prices must reflect the Value of the Lost Load (VoLL) in case of a power cut. Although estimates of the VoLL vary considerably across studies and change across countries and over time, it is generally considered to be well above 3,000 euros per MWh. Regulatory authorities and system operators are unlikely to allow those spikes to occur for a variety of well-documented reasons, like the protection of inelastic-demand consumers. As a result, price caps are in actuality substantially lower than the VoLL.[3]

However, an energy-only market where prices are capped well-below the VoLL is bound to suffer from underinvestment in capacity due to its under-remuneration. Shanker (2003) named this result the *missing-money* problem and it arises both when producers are price takers (see, for example, Cramton and Stoft (2006) or Bajo-Buenestado (2017)) and when there is a limited number of strategic firms (see, for example, Zottl (2011) or Bajo-Buenestado (2017)).[4] The effect of price caps on investment is not necessarily monotonic. Zottl (2011) calibrates his model using German data and shows that, under oligopoly, lowering the price caps does not necessarily reduce investment.

The risk and cost of blackouts might also be a source of underinvestment if they generate and externality that firms do not consider in their investment decisions. As Keppler (2017) emphasizes, however, blackouts must be involuntary in the sense that transaction costs must prevent users and firms from adapting to their existence. Externalities will exist if the service cannot be perfectly curtailed according to the consumer willingness to pay.[5] These externalities might also be a reason behind the political concerns regarding blackouts.

2. The short-run complementarity of renewable and conventional power sources has also been noted in other theoretical papers such as Ambec and Crampes (2012). However, in their model it arises when prices cannot adjust to changes in supply due to the unavailability of smart meters. This effect is not present in our model, since we assume that prices adapt to market conditions.

3. See Table 1 in European Commission (2016) for a comparison of VoLL estimates and price caps for a variety of European countries. Price caps in many US regional markets are set at $1000 per MWh (FERC, 2016)

4. In Shanker's words

> I refer to the difference between revenues generated by the current market and revenues that are needed to both motivate new entry in the market and properly compensate existing resource adequacy suppliers as the "missing money"

As Keppler (2017) points out, the term "missing money" is often used incorrectly to identify situations in which generators would not recover their investment cost in equilibrium. This situation would never occur in markets under free entry and exit.

5. This point is also discussed in Joskow and Tirole (2007). They show that when capacity is insufficient to meet demand, efficient investment requires retailers to have the technology to curtail the service only of price-insensitive consumers (e.g. consumers without smart meters), while the rest of consumers face higher prices that endogeneously reduce their demand.

Capacity payments have emerged as the main mechanism to foster efficient investment when energy-only markets fail to deliver it and their design has been discussed in previous papers like Cramton and Ockenfels (2012). There is also consensus that capacity payments should be set through capacity auctions designed so as to provide the right investment incentives to both incumbents and new entrants without remunerating market power (see, for example, European Commission (2016)). Although these out-of-market payments are often considered only for capacity available to cover peak demand, in recent years they have also been proposed to compensate base-load capacity, including nuclear and coal-powered plants. However, Briggs and Kleit (2013) show that capacity payments in this case are difficult to justify from an efficiency point of view.

The interaction between capacity payments and other regulation has also been studied. For example, Bajo-Buenestado (2017) calibrates his model to the Texas electricity market and shows that capacity payments can be a counterweight to price caps. They contribute to diminish the probability of blackouts although the ensuing payments reduce consumer surplus. Similar trade-offs emerge in papers like Joskow and Tirole (2007) or Léautier (2016).

An implicit assumption in all capacity auction models analyzed in the literature as well as those implemented in practice, and one that is of crucial importance for the optimality of the auction mechanism, is that the regulator implementing a capacity auction commits not to provide out-of-market finance for the entry of additional capacity once the capacity auction has been concluded (or in a dynamic setup where capacity auctions are repeated over time, during the period between scheduled capacity auctions). That is, the capacity auction determines both the amount of capacity available in the market as well as its remuneration; no capacity is allowed to enter the market outside the auction framework, i.e. ex-auction.[6]

In practice, ex-auction renewable capacity increases might occur due to several reasons. Our model suggests that this entry might be justified due to ex-post efficiency considerations when the share of the fixed costs of conventional power producers that can be recovered upon exit is either very large or very small. In other cases, the increase in capacity is the unavoidable consequence of environmental and industrial policy objectives that take precedence over the (narrower) goals of energy policy and may occur even it is not efficient ex post.

Because increases in capacity outside the auction framework lead to a lower wholesale electricity price and a reduction in the number of hours during which the back-up conventional plants operate, they increase consumer surplus in the short term (albeit only to the extent that the reduction in generation prices is passed on to consumers in the form of lower retail prices), at the cost of distorting investment and, therefore, long-run productive efficiency. Our model suggests that this trade-off between long-run costs and short-term consumer surplus gain is of particular relevance when the redeployment value of conventional power plants is low. When that is the case the long-run implications of ex-auction entry will be significant: potential bidders in future capacity auctions will take into account the risk of ex-post increases in capacity and will price that risk in their bids. This risk will increase the cost of electricity in the long term, either because consumers will have to bear the cost of increased capacity payments or because they may be exposed to scarcity pricing or blackouts if participation in the capacity auction is reduced.

We show that fine-tuning capacity payments ex post may have the potential to resolve the two problems that ex-auction renewable power increases might generate. First, they may adjust the compensation of conventional power producers, restoring the credibility of the system. Second, they

6. We denote those capacity increases that take place after the auction as ex-auction rather than post-auction increases because in practice capacity auctions may be repeated over time. The term ex-auction capacity increase thus means increases in capacity that take place outside (ex in latin) the auction mechanism.

may be supplemented to foster the ordered exit of the excessive capacity that the entry of renewable power plants might bring about.

We propose a solution involving two complementary mechanisms. In some cases, decommissioning conventional power plants after entry is not necessary. In that case, Governments ought to commit to increase the capacity remuneration received by all plants selected in the capacity auction in case of an ex-auction increase in renewable capacity. The incremental payment could be determined by means of a counterfactual ex-post capacity auction, according to which these plants would receive the same payment that would have resulted from the capacity auction with a level of capacity that includes the ex-auction increase in capacity and a level of demand and costs equal to their ex-ante levels.[7] In other instances it might be optimal to remove from the market some idle thermal plants. In order to do that we propose an ex-post capacity auction that includes an exit payment, which *de facto* introduces a minimum reserve price.

Our mechanisms have a simpler implementation than ex-ante schemes which, although more general, should consider remunerations in states of the world that are difficult to determine. However, we also acknowledge that they imply some challenges that need to be addressed in terms of information requirements and the need to adjust the capacity remuneration to avoid compensations for the demand and cost risks associated to the normal course of business.

The reminder of this paper is organised as follows. In Section 2 we describe the economic model we use for our analysis. In Section 3 we analyze the short-run and long-run effects of increasing capacity outside the auction i.e. ex-auction, and why they undermine the credibility and efficiency of capacity mechanisms. In Section 4 we describe the two auctions we propose to restore the credibility in the capacity auctions. Section 5 discusses the effects of market power and section 6 concludes.

2. THE MODEL

Consider a wholesale electricity market in which the demanded quantity q is uncertain and independent of the price. It arises from a distribution $G(q)$ with full support $[0,\infty]$ and density $g(q)$. As a result, $1-G(q)$ is the inverse of the standard *load-duration curve*, since it indicates the percentage of hours that demand exceeds a level q.[8]

Suppose that in the market there is an amount K_R of renewable capacity and K_C of conventional power (e.g. Combined Cycle Gas Turbine or CCGTs). The former has a marginal cost of 0 and a fixed cost of F. The latter has a marginal cost $c>0$ and a total fixed cost fK_C. As it will become clear later, f might include not only fixed costs but also entry costs.[9]

We assume that firms behave competitively.[10] This implies that if capacity is enough to cover demand, the price p is set by the marginal cost of the last production unit. If capacity is not enough, however, we assume that all units receive a remuneration set by a price cap $\overline{p}\geq c$. Given

7. We denote this as a counterfactual ex-post auction because it is conducted ex-post involving the level of capacity that prevails after the ex-auction increase.

8. In our setup the percentage of hours a plant is operating and the probability it operates are equivalent and we will use both terminologies indistinctively.

9. The asymmetry in the treatment of the fixed cost of renewable and conventional power plants is made for presentation and computational purposes. Since the focus of the paper is in the choice of conventional power we model its costs as a linear function of K_C. The amount of renewable power will remain constant and, thus, we just need to define the total cost of K_R capacity.

10. In Section 5 we discuss the effects of market power.

that renewable units have a lower marginal cost and they are dispatched first, the expected price can be written as

$$E(p) = c\left[G(K_C + K_R) - G(K_R)\right] + \overline{p}\left[1 - G(K_C + K_R)\right].$$

The previous expected price results from the consideration of three cases. With probability $G(K_R)$ only renewable power will be used, leading to a price of 0. The price will be c when both sources of energy are enough to cover the demand, which occurs with probability $G(K_C+K_R)-K_R$. Finally, the price will be $\overline{p}$ when demand exceeds total capacity, which occurs with probability $1-G(K_C+K_R)$. Notice that, as a result, the expected price is decreasing in K_R for two reasons. First, a higher K_R makes the price 0 more likely, since it increases the probability that the marginal plant uses renewable energy. Second, the price $\overline{p}$ arises less often, since excess demand is less likely. In contrast, notice that when K_C increases, the price is reduced due only to the second effect.

For a given demand q the probability that a unit of conventional power is dispatched (assuming that all units offered at the same price are dispatched with the same probability) can be written as

$$J(q, K_R, K_C) = \begin{cases} 0 & \text{if } q < K_R, \\ \dfrac{q - K_R}{K_C} & \text{if } K_R \leq q < K_R + K_C, \\ 1 & \text{if } q \geq K_R + K_C. \end{cases}$$

Following the previous discussion, when $q < K_R$ demand can be met with renewable sources and no conventional power plant will be dispatched. At the other extreme, when demand exceeds total capacity all conventional power plants will be dispatched. In between, when not all conventional power plants are necessary, they have the same probability of being dispatched. This probability is then decreasing in K_R and K_C.

Thus, expected profits of a conventional power producer with capacity k can be computed as

$$\Pi(k) = \left[(\overline{p} - c)(1 - G(K_C + K_R)) - f\right]k.$$

This expression indicates that only when demand exceeds total capacity, which occurs with probability $1 - G(K_C + K_R)$, a conventional power plant will receive a remuneration above the marginal cost c. In the other cases, either the plant is not dispatched or it receives a price exactly equal to its marginal cost.

Whether profits $\Pi(k)$ are positive or negative depends not only on the per-unit fixed costs but also on the total capacity installed. The higher is $K_C + K_R$ the lower these profits become. Under free entry, the equilibrium conventional capacity, K_C^c, will solve the expression

$$(\overline{p} - c)(1 - G(K_C^c + K_R)) = f. \tag{1}$$

For the reasons that we discuss later, this capacity might not always be socially desirable.[11] Governments might intervene and induce any total capacity $K \geq K_R$ using a per-unit capacity payment $t(K)$, defined as

$$t(K) = f - (\overline{p} - c)(1 - G(K)). \tag{2}$$

11. See also footnote 4.

This payment is increasing in the total capacity targeted. This result is quite intuitive since it means that when more capacity is available, the expected price in the market is lower and the probability that any given plant is dispatched decreases.

Different capacity mechanisms might induce the same allocation of capacity $K \geq K_R$ if they induce the same payment $t(K)$. In some cases, these payments are administratively set by the regulator. In other cases, the regulator designs an auction among potential entrants in which it credibly commits to limit the added capacity to $K - K_R$. Under competition, the equilibrium will result in a payment that makes firms indifferent between investing or not. In other words, firms will bid $t(K)$. It is widely understood that auctions are preferred due to their lower information requirements.

2.1 Optimal Conventional Capacity

The equilibrium conventional capacity that the market delivers, K_C^c, might not be socially optimal due, for example, to a low price cap or to the externalities that power cuts might bring about. These cases justify the establishment of capacity payments, as we show in this section.

We assume that consumers have a per-unit valuation $v \geq \overline{p}$.[12] We also assume that the government maximizes total welfare, understood as the sum of consumer surplus and firm profits.[13] However, as it is well known, and given the competitive nature of the market, the results would be unchanged if consumers had a higher weight in the social welfare function (see Armstrong and Sappington, 2007)).

For a given renewable capacity K_R, we can define the socially optimal K_C^* as the solution to

$$\max_{K_C} \int_0^{K_R} vqg(q)dq + \int_{K_R}^{K_R+K_C} \left[vq - c(q-K_R)\right] g(q)dq$$
$$+\left[v(K_C+K_R) - cK_C\right]\left[1-G(K_C+K_R)\right] - fK_C - F. \quad (3)$$

The first three terms of this welfare expression account for the gross surplus generated by each unit consumed, v, depending on whether it is produced with renewable sources only, it also includes conventional power, or capacity is not enough to meet demand. The cost of capacity is deducted from this expression. The marginal cost is 0 when $q \leq K_R$ and equal to c for the additional demand. The final two terms are the investment costs. The next lemma characterizes the solution to this problem.

Lemma 1 *The socially-optimal conventional capacity,* K_C^**, is* 0 *if* K_R *is sufficiently large so that* $(v-c)(1-G(K_R)) \leq f$ *and it is implicitly defined as*

$$(v-c)(1-G(K_C^*+K_R)) = f, \quad (4)$$

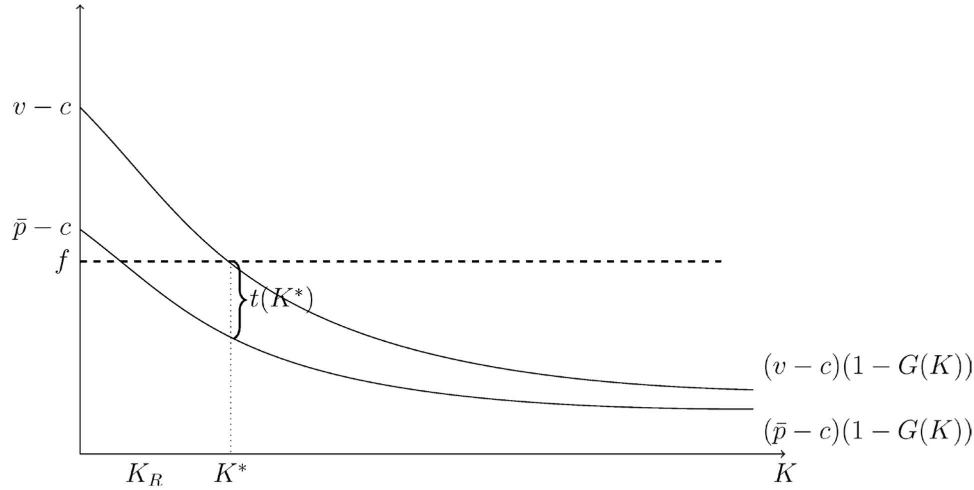
otherwise. This capacity is increasing in v and decreasing in c and f.

The interpretation of this result is standard. The marginal unit of conventional power must lead to an expected social welfare gain, understood as $v-c$ times the probability that it operates, equal to the additional cost of that capacity, f. Thus, the socially optimal total capacity $K^* \equiv K_C^* + K_R$ is independent of the existence of renewable plants, as long as K_R does not already exceed K^*.

12. This valuation denotes the willingness to pay of consumers for load and, thus, it approximates the VoLL, and equals it in the absence of externalities.

13. In this paper we use the term government and regulator interchangeably since we are not modeling their potentially different motivations and the ensuing principal-agent problem.

Figure 1: Capacity choice and capacity payments when $(v-c)(1-G(K_R))>f$



This result, of course, implies that K_C^* decreases one to one with increases in K_R.[14] Following Zottl (2011), our result also generalizes to the case with multiple base-load technologies—like coal or nuclear power—that are dispatched before the peak-load conventional capacity considered here, since the trade-off between them is driven by their relative fixed and marginal costs.

Figure 1 shows that in the socially optimal capacity choice conventional producers must receive a remuneration per unit of capacity $(v-\overline{p})(1-G(K^*))\geq 0$ in order to be willing to enter the market. That is, when $v>\overline{p}$, the marginal return to capacity that a competitive firm receives under free entry and free exit, $(\overline{p}-c)(1-G(K^*))$, is lower than the social return, $(v-c)(1-G(K^*))$. This difference is what the literature has denominated a *missing-money* problem and is, again, the result of a price cap $\overline{p}$ that, as discussed in the introduction, is typically below the VoLL, v. The positive payment that conventional producers should receive in order to provide the efficient capacity to the market is

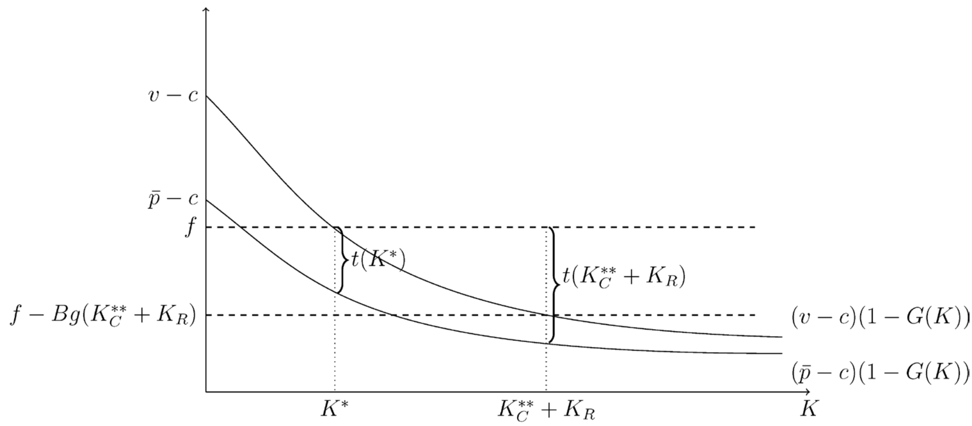
$$t(K^*)=f-(\overline{p}-c)(1-G(K^*))>f-(v-c)(1-G(K^*))=0.$$

Of course, this is not the only reason why firms in a market with free entry and exit may not be willing to provide the socially efficient capacity in the absence of capacity payments. A similar problem arises when the regulator aims to foster investment to achieve a capacity level $K_C>K_C^*$, even if $\overline{p}=v$. One of the most salient reasons to set a higher capacity is the aim to prevent blackouts. Increasing capacity beyond K_C^* might be justified in pure efficiency terms if blackouts generated a social cost beyond the loss in surplus, v. For example, they might entail disruptions to third parties, with a per-unit cost b, that consumers do not take into account in their purchasing decisions (see Keppler (2017)). In that case, the net value of production would be $v+b-c$ and the optimal capacity would result from

$$(v+b-c)(1-G(K_C^{**}+K_R))=f,$$

14. This result hinges on the assumption that both renewable and conventional power is firm. As we will see in section 2.2, once we account for the volatility of the former, an increase in K_R should lead to a less than proportional decrease in K_C^*.

Figure 2: Effect of blackout costs on capacity payments



with K_C^{**} increasing in b. Notice that a positive value of b originates a wedge between the valuation of consumers and the price that firms receive for their production, generating the same underinvestment problem created by a price cap.

Interestingly, the previous interpretation can also accommodate instances in which conventional power entails negative externalities that are not included in the marginal cost c. These additional effects (e.g. pollution) would operate in the model as a negative value of b. Notice that in this case underinvestment would arise if and only if $v+b>\overline{p}$.

Alternatively, one may suppose that the mere existence of blackouts might also create reputational costs for the government above and beyond the externality created to consumers. In the benchmark case, the expression in Lemma 1 implies that it is socially optimal to allow blackouts with probability

$$1-G(K_C^*+K_R)=\frac{f}{v-c}.$$

Governments and/or regulators might be concerned that this loss undermines their credibility. If we denote the reputational cost of a blackout as $B\geq 0$, the social welfare function described earlier ought to include now a new term $-B[1-G(K_C+K_R)]$. From the first-order condition of the problem we can characterize the optimal capacity in the next result.

Lemma 2 *Under a reputational cost of blackout cost B, when $K_C^*>K_R$, the optimal capacity K_C^{**} results from*

$$(v-c)(1-G(K_C^{**}+K_R))=f-Bg(K_C^{**}+K_R),$$

increasing in B and v and decreasing in c and f.

As indicated in Figure 2, $K_C^{**}\geq K_C^*$, reducing the probability that demand cannot be met with the installed capacity. Of course, this figure also illustrates that such an increase in capacity implies a larger capacity payment: $t(K_C^{**}+K_R)>t(K^*)$, meaning that the effects are very similar those studied in the previous case.

The next proposition summarizes the previous results.

Proposition 3 *The total conventional capacity that maximizes social welfare will exceed the one that competitive firms will provide if*

1. *price caps are binding and/or*
2. *there are negative externalities from blackouts,*

and the negative externalities from conventional power plants are not very large.

As anticipated, the payment that will implement the capacity K resulting from the previous proposition can be obtained from equation (2). This payment, $t(K)$, will be positive if and only if the capacity is higher than the one that firms would choose without intervention.[15] Since the implications under the different scenarios summarized in Proposition 3 are very similar, in the rest of the paper we focus our discussion, for the sake of simplicity, on the case in which price caps are binding.

2.2 Volatility of Rewewable Production

The quotation in the introduction from the report on capacity mechanisms published by the European Commission in 2016 emphasizes the importance of accounting for the volatile nature of renewable sources like wind or solar power. The report stresses the increasing role of capacity payments to plants providing firm power as renewable sources become more prevalent. In this section we explicitly consider the volatility of renewable power and show that, under reasonable assumptions, these claims are substantiated by the results of the model. Conventional capacity is more necessary in the presence of volatile renewable plants, increasing the need for capacity payments.

Consider the baseline model discussed in the previous section. Assume now that the availability of renewable plants is subject to fluctuations. In particular, denote as $\overline{K}_R$ the installed renewable capacity (often known as *nameplate* capacity). Due to its inherent volatility, only a proportion $\theta \in [0,1]$ of this theoretical capacity will turn into production, $\theta\overline{K}_R$. We assume that the parameter θ arises from a distribution $H(\theta)$ with density $h(\theta)$ and denote the average (or expected) renewable production as $K_R \equiv E(\theta)\overline{K}_R$.

Using the same arguments discussed before, the optimal choice of conventional capacity, K_C^*, can be characterized as the solution to the following problem

$$\max_{K_C} \int_0^1 \left\{ \int_0^{\theta\overline{K}_R} vqg(q)dq + \int_{\theta\overline{K}_R}^{\theta\overline{K}_R+K_C} \left[vq - c(q-\theta\overline{K}_R) \right] g(q)dq \right.$$
$$\left. +\left[v(K_C+\theta\overline{K}_R) - cK_C \right]\left[1-G(K_C+\theta\overline{K}_R) \right] \right\} h(\theta)d\theta - fK_C - F. \quad (5)$$

This expression is identical to the one described in equation (3) except that we now need to account for all the possible availability levels of renewable production $\theta\overline{K}_R$. This problem results in the following first-order condition

$$\int_0^{\infty} (v-c)(1-G(\tilde{K}_C+\theta\overline{K}_R))h(\theta)d\theta = f,$$

which indicates that the last unit of conventional capacity, $\tilde{K}_C$, should lead to an expected social gain equal to its installation cost. How does this optimal capacity compare to the one described under no volatility, K_C^*? In order to respond to this question we start with a more general result.

15. Interestingly, in section 5 we show that under some circumstances this capacity payment would also be optimal if all conventional power was owned by just one or a few firms.

Proposition 4 *Consider two alternative renewable tecnologies* $i = 1,2$ *with distribution functions* $H_1(\theta)$ *and* $H_2(\theta)$*, with the same expected production,* K_R*, but where* $H_2(\theta)$ *second-order stochastically dominates* $H_1(\theta)$*. If* $G(p)$ *is concave, the welfare maximizing conventional capacity,* $\tilde{K}_C$*, is higher under* $H_2(\theta)$*.*

Notice that the strict concavity of $G(q)$ is satisfied if, for example, $g(q)$ is decreasing in q, meaning that a larger demand is less likely to arise than a lower one. Under this assumption, we can reach the following conclusion. Suppose we compare the case in which renewable power K_R is firm (a degenerate distribution H_1 in the previous proposition) with the case in which it is volatile (distribution H_2) but it has the same expected production. The result indicates that in this latter case it is optimal to install more conventional power. The reason is that the fluctuation of the latter might be useful to meet high demand requirements when production is high, at the cost of sometimes not being able to satisfy lower demands when production is low. The overall effect of this volatility is negative because when $g(q)$ is decreasing, the gains from having access to a large production accrue less often than the losses from not being able to serve a smaller demand. To cover this risk it is socially optimal that the total conventional capacity expands compared to the case in which renewable production is constant.

The previous clear-cut result hinges on the assumption that $G(q)$ was concave. This assumption is uncontroversial when we consider that instances of sufficiently high demand are relatively infrequent and $g(q)$ decreases in that range. It is also true that cases of very low demand are also very unlikely and, therefore, the density increases in q in the lower region. Notice, however, that this part of the distribution is less affected by the volatility of renewable production, since it will be already covered with conventional power sources. In other words, in the lower part of the distribution, the volatility of renewable production would not affect the quantity supplied but only the marginal cost of its provision, limiting its scope to increase efficiency. Thus, the result in Proposition 4 should carry over to situations where $G(q)$ is not globally concave, provided that $g(q)$ is decreasing when q is large and renewable power is critical to satisfy the demand.

Futhermore, the previous mechanism is more likely to operate in relation to gas-powered plants or CCGTs than in connection to other technologies that also provide firm power. Since CCGTs usually cover peak-load demands, as opposed to nuclear and coal-fired plants that have been traditionally used for base-load production, they become the closest substitute to renewable sources when their volatility makes them unavailable. This intuition is consistent with the empirical work of Cullen (2013), who finds that wind production crowds out only CCGTs while it has no effect on coal-fired power plants. In other words, when wind does not blow the production from windmills is mainly replaced by natural gas plants.

That paper also illustrates that, whereas in our model the distribution function of demand and renewable power availability are independent, in practice they are often correlated. In particular, he shows that this correlation is negative in the case of windmills, which produce more at night, due to stronger winds. It is easy to see that this negative correlation reinforces the previous results, since it makes situations of large demand and high availability less likely, reducing the usefulness of the volatile renewable power sources.[16]

Needless to say, the previous proposition also applies more broadly to the comparison of different renewable technologies that have the same expected production but different levels of

16. It is also likely that the correlation is positive for solar panels that produce mainly during the day, weakening for that technology the effect we uncover here.

volatility. A more volatile technology will require more back-up firm capacity to cover for possible shortfalls.

We close this section by drawing implications for the capacity payments under volatility of renewable production that follow from the previous proposition.

Corollary 5 *When $G(q)$ is strictly concave in q, capacity payments are higher if, for a given average production, renewable production becomes more volatile.*

The conditions under which renewable capacity is less useful to guarantee the supply when it becomes more volatile, also imply that more conventional power is necessary and, as a result, capacity payments should increase too. The impact of the volatility of renewable energy on the optimal K_C will be additive to the effects that we highlight in the rest of the paper. For this reason, and in order to simplify the exposition, we conduct the rest of the analysis under the assumption that the renewable production is firm.

3. EX-AUCTION CAPACITY INCREASES

We now consider the effects of an exogenous increase in renewable capacity. We start from a situation in which, originally, the efficient capacity level K^* was reached, through the use of a capacity auction. For simplicity we assume that $K_R = 0$, so that $K_C^* = K^*$ as defined in (4). Suppose that, once the investment in conventional capacity is sunk, the government increases total renewable capacity available. In particular, we move to a situation with $K_R > 0$ renewable capacity. This capacity enters the market after the auction, i.e. ex-auction. That is, the government reneges on its commitment to limit total capacity to K_C^*. This may be the result of regulatory opportunism—i.e. the government takes advantage of the sunk investments made by conventional power producers to introduce and/or expand renewable capacity in order to depress prices and increase reliability—or the consequence of environmental and/or industrial policy decisions that conflict with the energy policy choices made at the time of the initial capacity auction.

In order to simplify the exposition, and consistent with the discussion in the previous section, we assume that renewable capacity is not volatile and that there are no externalities. So, the only possible source of inefficiency prior to the entry of renewable power is the existence of a price cap. Allowing for these two features of the market in the model would deliver similar results as we briefly discuss later in the text.

We assume that after the entry of renewable production, each unit of conventional capacity can be decommissioned with a redeployment value γf, with $\gamma \in [0,1]$. This redeployment value includes the value of the assets if deployed somewhere else and/or the savings in fixed costs. In other words, the remaining $(1-\gamma)f$ are sunk costs, in part incurred at entry.[17]

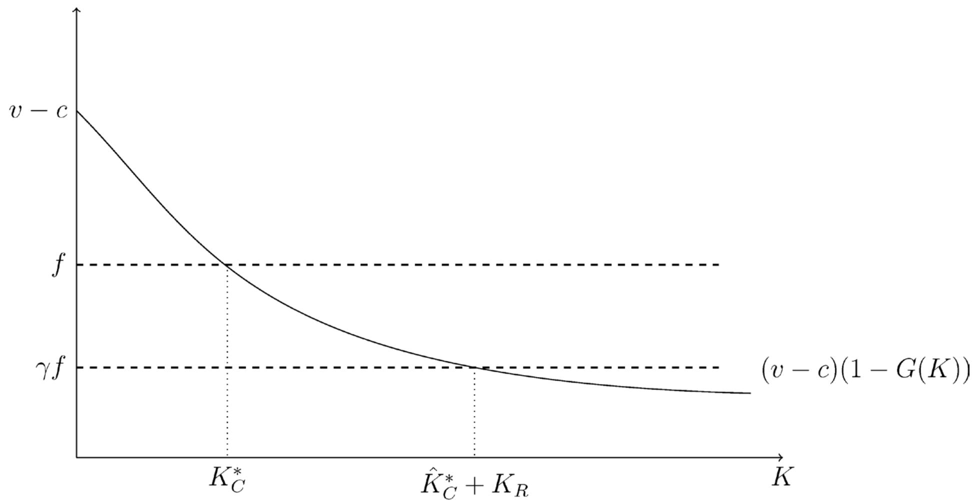
How the capacity from conventional sources is optimally adjusted, through exit, from K_C^* to $\hat{K}_C$, is determined as the result of the following problem.

$$\max_{\hat{K}_C \le K_C^*} \int_0^{K_R} vqg(q)dq + \int_{K_R}^{K_R+\hat{K}_C} \left[vq - c(q-\hat{K}_R)\right] g(q)dq$$

$$+\left[v(K_R+\hat{K}_C) - c\hat{K}_C\right]\left[1-G(\hat{K}_C+K_R)\right] - fK_C^* + \gamma f(K_C^* - \hat{K}_C). \quad (6)$$

17. The redeployment value γf includes fixed operation costs that can be avoided upon exit (which might be as high as one sixth of the annualized total cost), as well the as the value of turbines and other electric equipment when reused in other installations. The value of land might also increase as some of the infrastructure built for a CCGT plant might be valuable for other production (e.g. water or power supply).

Figure 3: Ex auction increase in capacity



This welfare expression is similar to the one obtained in the benchmark case but it now accounts for the redeployment value that retiring conventional power plants has in terms of fixed cost savings. The next proposition characterizes the solution to this problem.

Proposition 6 *The optimal conventional capacity after the ex-auction entry of K_R renewable power, $\hat{K}_C^*$, is equal to the minimum between K_C^* and the solution to*

$$(v-c)(1-G(\hat{K}_C+K_R))=\gamma f. \quad (7)$$

This optimal capacity is weakly increasing in γ.

In order to interpret this result ignore, for the moment, the constraint $\hat{K}_C \le K_C^*$, so that the first-order condition of the previous problem determines the optimal capacity, defined as

$$(v-c)(1-G(\hat{K}_C^*+K_R))=\gamma f. \quad (8)$$

This capacity choice is illustrated in Figure 3. Notice that the higher is γ the lower is $\hat{K}_C^* + K_R$ meaning that less conventional power will be used after the entry of renewable plants. As a result, there is a threshold $\underline{\gamma}$ such that, as long as $\gamma \ge \underline{\gamma}$, some capacity will be retired from the market. Otherwise, when the redeployment value is lower than $\underline{\gamma}$, all the already installed capacity should remain in operation. In the limit, when $\gamma = 0$, we know that retiring conventional capacity would never be optimal. At the other extreme, when $\gamma = 1$, the expression becomes identical to (4) meaning that when there are no sunk costs, the introduction of renewable capacity should be accompanied with a one-to-one decommissioning of conventional power plants.[18]

When is the increase in renewable capacity and the associated downward adjustment in conventional capacity optimal from a social standpoint? For simplicity, we have originally assumed that K_R renewable capacity could be incorporated at a total cost F. The comparison when renewable power is introduced (and conventional capacity is adjusted accordingly) with a situation where $K_R = 0$ results from comparing (3) and (6) and it yields the following change in welfare

18. We implicitly assume that K_R is not too large, so that it is never optimal to retire all the conventional power capacity.

$$\int_{K_C^*}^{K_R+\hat{K}_C^*}(v-c)qg(q)dq+(v-c)\left\{(\hat{K}_C^*+K_R)\left[1-G(\hat{K}_C^*+K_R)\right]-K_C^*\left[1-G(K_C^*)\right]\right\}$$
$$+cK_R(1-G(K_R))+\int_0^{K_R}cqg(q)dq-F+\gamma f(K_C^*-\hat{K}_C^*). \quad (9)$$

In the previous expression the first two terms correspond to the increase in gross surplus due to the expansion of capacity from K_C^* to $\hat{K}_C^*+K_R$ if this increase were conducted with conventional power. The following two terms are marginal cost savings from renewable sources net of the fixed costs of installing them. The last term corresponds to the redeployment value of the conventional power plants that are retired from the market.

It is important to notice that, due to Lemma 1, the first two terms are smaller than $f\times(K_R+\hat{K}_C^*-K_C^*)$. That is, if the capacity increase were carried out with conventional power plants the costs would not compensate the benefits generated. This result allows us to compute the following necessary condition—albeit not sufficient—for the addition of renewable power to be socially profitable:

$$F-cK_R(1-G(K_R))-\int_0^{K_R}cqg(q)dq<f\left[K_R-(1-\gamma)(K_C^*-\hat{K}_C^*)\right]. \quad (10)$$

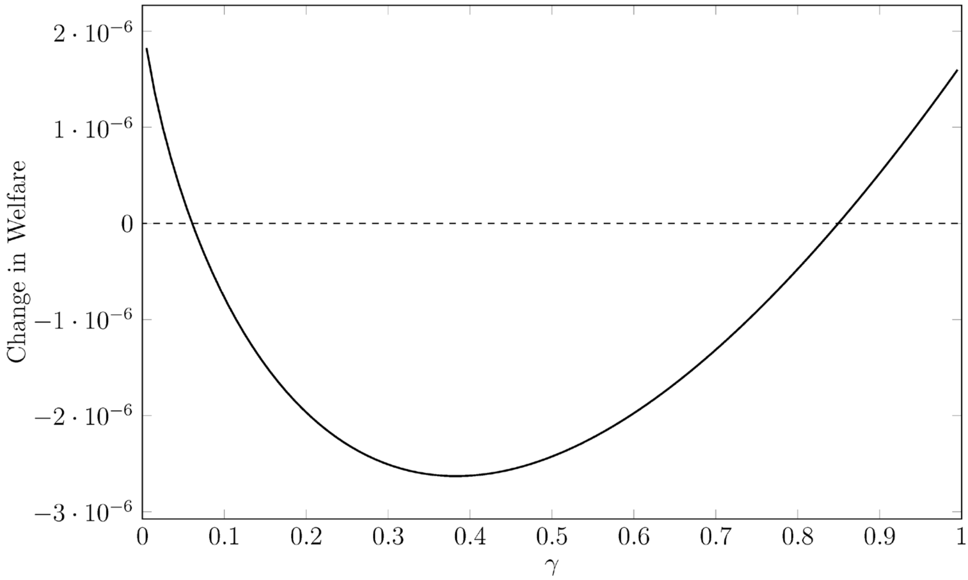
This expression has a simpler interpretation, particularly if we consider the situation in which exit is costless, $\gamma=1$. In that case, a necessary condition for adding capacity K_R with renewable power to be socially optimal is that the total cost of installing it, F, net of the costs savings that it entails in terms of marginal costs is lower than the cost of having built that capacity using conventional power plants, fK_R. When $\gamma<1$, retiring conventional power plants is costly, leading to two additional effects. First, the lower is the redeployment value the higher will this cost become and, as a result, the more efficient should be the renewable power and/or the lower should be the building costs F to make the investment socially worthwhile. This effect implies that inequality (10) is less likely to hold when γ is small. Second, the size of the adjustment, $K_C^*-\hat{K}_C^*$, is increasing in γ. This implies that, as we have seen, in the limit when $\gamma=0$, it is not optimal to reduce capacity (i.e. $K_C^*=\hat{K}_C^*$) and therefore no additional social cost is incurred. As a result, when both effects are considered, inequality (10) is less likely to hold when γ takes an intermediate value. An example of this result is illustrated in Figure 4.

Ex-auction capacity increases generate a negative externality on the owners of conventional power plants that entered in the auction: the capacity payments they were awarded are insufficient to break even given the negative impact that the increase in capacity has on the market price and the utilization of their plants. However, the previous discussion indicates that the government will typically have an incentive to increase capacity ex-auction in the two extreme cases, when γ is relatively large or relatively low, with different implications. When γ is large enough and the proportion of the conventional power plants' fixed costs that are sunk is low, the ex-auction capacity increase is not only socially optimal in the short-term but it will also have little adverse impact on the owners of conventional power plants that entered the market at the capacity auction, as they will be able to recover most of their entry costs. On the contrary, when γ is small the increase in capacity ex-auction will have a significant negative impact on the owners of conventional power plants. In other words, using (2) and (8), we have that when $v>\overline{p}$ and $\gamma<1$,

$$(\overline{p}-c)(1-G(\hat{K}_C^*+K_R))+t(K_C^*)-f<-(1-\gamma)f,$$

indicating that, under free entry and exit, some conventional power producers will find optimal to leave the market.

Figure 4: Example of the change in welfare resulting from the introduction of renewable capacity



Note: This example assumes that $G(q)=1-e^{-\alpha q}$ and uses parameter values $c=0.05$, $f=0.1$, $K_R=0.12$, $F=0.013$, and $\alpha=8$.

Furthermore, to the extent that the introduction of renewable capacity fosters a decrease in prices, it implies a redistribution of surplus from producers to consumers. It is in the case in which γ is very low (or zero) that this effect will be strongest and with it, the risk of regulatory opportunism. The introduction of renewable capacity in this case is likely to undermine the credibility of the capacity auction and, consequently, to compromise the potential of this mechanism to solve the missing-money problem. In practice, this is an important situation since often the decommissioning of production plants requires government permission, implying that conventional capacity is forced to remain in the market at a loss.

Finally, notice that allowing for environmental motivations, other externalities, or industrial-policy reasons would just enlarge the range of values of γ for which renewable entry is optimal. Similarly, accounting for the volatility of renewable production along the lines of our discussion in section 2.2 would have the opposite implications.

4. RESTORING THE CREDIBILITY OF THE CAPACITY AUCTION

Forward-looking governments should take into account the dynamic implications of ex-auction capacity increases by introducing ex-post compensation schemes that restore the credibility of the capacity auction mechanism, particularly when γ is below 1. By adjusting the payments made to the owners of plants that entered at the time of the auction, the government corrects the negative externality created by the ex-auction capacity increases. These capacity expansions may still occur but they are less likely to be driven by regulatory opportunism and they will not compromise the realization of future auctions.

Ideally, a capacity mechanism would contemplate, at the initial stage when conventional capacity is built, all the possible scenarios that may arise and in which renewable power would be introduced ex-auction in the market. Of course, implementing such a contract would represent an enormous challenge as it implies anticipating all possible contingencies that could arise.[19]

For that reason, we propose an alternative way to restore the credibility of the capacity mechanism ex-post, based on the commitment by the government to compensate firms when ex-auction entry occurs according to a pre-specified rule. We also discuss the challenges and limitations of this approach.

4.1 Ex-Post Capacity Mechanisms

The optimal conventional capacity after the ex-auction entry of renewable power characterized in the previous section indicates that the decision to decommission conventional power plants or not hinges on the redeployment value γ. If γ is low, it would be optimal not to retire any capacity. If γ is high, all extra capacity beyond $\hat{K}_C^* + K_R$ should be induced to leave the market. Thus, the optimal intervention must at the same time restore the credibility of the capacity auctions while it induces the exit of excessive capacity. In this section we show that achieving both goals requires that the regulator combines two different mechanisms.

If γ is low, the solution to the credibility problem is simple as it does not require any change in the total capacity. It is only necessary to legally commit to increase the unit capacity payment set in (2) from $t(K_C^*)$ to $t(K_C^* + K_R)$ in response to the entry of renewable capacity K_R. The higher capacity remuneration equals the capacity remuneration that would result from a capacity auction following the entry of K_R, i.e. ex post, for a level of capacity $K_C^* + K_R$.

The situation when the redeployment value γ is higher is more interesting since it requires some capacity to be decommissioned from the market. In order to do that we propose an ex-post capacity auction. However, before discussing the precise implementation of this ex-post auction, let us start by considering a case in which conventional power producers receive a (potentially negative) payment when they stay in the market, denoted as t_S, or when they exit, t_E. In order for $K_C^* - \hat{K}_C^*$ units of capacity to be retired from production, it has to be that

$$\gamma f + t_E = (\overline{p} - c)(1 - G(\hat{K}_C^* + K_R)) + t_S. \tag{11}$$

This expression indicates that, per unit of capacity, conventional power producers must be indifferent between exiting the market and obtaining the redeployment value of their plants together with t_E or stay and obtain the market revenues together with a payment t_S.

Making use of (8) we obtain

$$t_S = \frac{v - \overline{p}}{v - c} \gamma f + t_E. \tag{12}$$

This expression implies that the payment to stay must be larger than the one producers receive to leave, $t_S \geq t_E$, if $v \geq \overline{p}$.[20] We can now verify under which conditions conventional producers would break even from an ex-ante point of view if they anticipate the entry of K_R units of renewable capacity and the corresponding downward adjustment in conventional capacity, provided they choose to stay in the market. Ex-ante profits per unit of capacity can be computed as

19. Standard capacity mechanisms rely on auctions that, in this case, would need to be multidimensional as firms would be asked to bid over their remuneration in all the states of the world. The design of such an auction would be extremely demanding.

20. A similar result would arise, for example, if there were externalities as discussed in Proposition 3.

$$\pi = (\overline{p} - c)(1 - G(\hat{K}_C^* + K_R)) - f + t_S = -(1-\gamma)f + t_E. \qquad (13)$$

That is, the owners of a conventional power plant will ex-ante break even if they receive a payment $\tilde{t}_E \equiv (1-\gamma)f$ per unit of capacity. The intuition is quite straightforward. After the entry of K_R units of renewable capacity, conventional power plants must be indifferent between staying and exiting the market. Those that exit will not produce and, therefore, will not receive any capacity payment. Yet, they will incur in a loss arising from their fixed costs, the part of f that cannot be recovered upon exit. Thus, firms will only break even if t_E makes up for this loss.

It is also important to notice that the capacity payment that a conventional power plant that stays in the market must recover to break even ex ante equals

$$\tilde{t}_S \equiv f - (\overline{p} - c)(1 - G(\hat{K}_C^* + K_R)) > t(K^*).$$

That is, capacity payments post entry must be higher than those resulting from the original capacity auction to adjust for the fact that conventional power producers face lower prices due to the operation of renewable sources. This is true even after capacity has been adjusted optimally.

The previous outcome can be implemented with a simple ex post auction mechanism. The regulator can set a payment $\tilde{t}_E = (1-\gamma)f$ if conventional producers exit the market. A clock-descending capacity auction can then be conducted. In this auction firms decide how much money they are willing to receive in order to stay in the market. The resulting bid in this auction will be $\tilde{t}_S$. It is important to notice that $\tilde{t}_E$ operates, de facto, as a "reservation price" in the auction. This price has a natural economic interpretation, since its existence internalizes the externality that the entry of renewable plants created on conventional power producers.

Finally, given the assumption made in this simple model that conventional power producers are identical is unlikely to hold in practice, the auction will optimally select which plants will leave the market and which ones will stay. In principle, the selection will take place within the auction mechanism, since the winners will be those bidders with lower marginal costs. However, the government may want to take into account their different contributions to the security of supply after the entry of the new capacity, especially if the new capacity is not firm, as discussed in section 2.2.

4.2 Implementation Challenges

From a policy perspective, a government seeking to implement the previous mechanisms faces several challenges, which would be common to other implementations. We now discuss some of these challenges and we assess their main risks.

First, establishing what constitutes new additional unexpected capacity increases is always bound to prove controversial. Investors and regulators may have different views as to what capacity should have been reasonably expected to enter ex-auction when the original auction was conducted. Formally, a government might argue that investors over-estimate the amount of unexpected renewable capacity, K_R. That is, it might dispute that it ever commited to limit capacity at K^* or it might argue that not all the capacity that entered the market was unexpected at the time of the auction but driven by known policy objectives (i.e. environmental goals) and, therefore, that ex-auction entry was a risk investors should have factored into their capacity remuneration requests. It is worth to notice that this problem is not specific to our mechanisms and although it could only be prevented if capacity increases were completely banned, this restriction would be undesirable from a social standpoint.

Second, the implementation of our mechanisms requires demand and cost information. This is particularly true when γ is low, as the mechanism implies calculating $t(K_C^* + K_R)$ without actually running an auction, which is an inherently difficult exercise. The regulator will need to estimate the impact that the entry of renewable capacity will have on market prices and on conventional capacity production and adjust the capacity payment according to equation (2). Payments would also need to account for ramping constraints and the uncertainty of revenues. These adjustments are complicated because they require to simulate the market results. When γ is high the informational requirements are much lower. The implementation of the mechanism requires only to set the reservation price for the auction, which depends only on the redeployment value of the plant (the part of the costs that is not sunk). This value could be approximated using the parameters of a standard plant.

Third, expected demand before the entry of renewable energy may not be equal to the expected demand after renewable entry. The same occurs with marginal costs for conventional power plants. In order to illustrate this effect, consider a slight generalization of our basic model and assume now that demand is distributed according to $G(q,\omega)$ and the marginal cost of the conventional plants is $c(\omega)$, where $\omega \in [\underline{\omega},\overline{\omega}]$ denotes an exogenous variable such as the state of the economy. If ω changes over time, then demand and cost conditions may also change, affecting also the optimal $K_C^* + K_R$.

When the change in market conditions is small, ignoring this effect is likely to be optimal as it saves on implementation costs. In other instances, however, a government seeking to ensure that its capacity auctions are credible might need to set the remuneration to reflect only the effects of the increase in renewable capacity, so that firms are not compensated twice for their standard business risk. Consider, for example, the case in which γ is low. Let ω_0 and ω_1 denote the expected state of the economy at the time of the capacity auction and the realized state of the economy after the entry of K_R capacity, respectively. Our mechanism prescribes that the capacity payment is increased from $t(K_C^*,\omega_0)$ to $t(K_C^* + K_R,\omega_0)$, where $t(K,\omega)$ denotes the capacity payment needed to solve the missing-money problem when capacity is K and the state of the economy is ω. Of course, $t(K_C^* + K_R,\omega_0)$ will typically be different from the ex post necessary payments for the conventional power producers to break even, $t(K_C^* + K_R,\omega_1)$. If $t(K_C^* + K_R,\omega_1) > t(K_C^* + K_R,\omega_0)$ firms would be compensated for their business risk.[21]

5. THE EFFECT OF MARKET POWER

A maintained assumption throughout the paper is that the market for conventional capacity is competitive and operates under free entry and exit. In this section we briefly discuss the implications of considering a limited number of firms and the market power it entails.

In particular, we consider the case in which a unique firm can invest in conventional capacity. Given an existing renewable capacity K_R, this firm will choose capacity to solve

$$\max_{K_C} \int_{K_R}^{K_C+K_R} (\overline{p}-c)(q-K_R)g(q)dq + (\overline{p}-c)(1-G(K_C+K_R))K_C - fK_C.$$

Interestingly, the capacity that this monopolist will choose, K_C^M, coincides with the one that a competitive market would provide,

$$(\overline{p}-c)(1-G(K_C^M+K_R)) = f,$$

21. The argument is slightly different when γ is large and exit is optimal. In that case, the exit payment should depend on current market conditions which is the risk that the firm avoids by not staying in the market. Using equation (13) this means that $t_E(K_C^* + K_R,\omega_1) = (\overline{p}-c)(1-G(K_C^* + K_R,\omega_1)) - \gamma f$ which is equal to $(1-\gamma)f$ if $\omega_0 = \omega_1$.

as long as K_R is not too large. This equivalence is due to the fact that, in both cases, the firm that carries out the investment in the marginal unit obtains all the return from this production. Of course, this equivalence does not imply that a monopolist makes 0 profits, as it is the result of competition among identical power producers. Under monopoly the average price is higher. As long as $q > K_R$ a monopolist will sell at a price equal to $\overline{p}$. In the competitive case, the price will only be equal to $\overline{p}$ when $q > K_R + K_C$, since for lower production market rents will be competed away and the price will equate marginal cost, c.

The previous discussion implies that the optimal capacity payment will coincide with the one we characterized in the benchmark model, $t(K)$, as defined in (2). As a result, the implications for the optimal capacity allocation will be identical to the ones obtained in the benchmark model. Absent ex-ante competition among potential producers, however, the implementation of the optimal allocation through capacity auctions would not be feasible.

Notice that the previous equivalence hinges on the assumption that consumer utility and firm profits are equally weighted in the social welfare function. As a result, higher prices and profits for the firm do not have an impact on welfare as long consumption and investment are not affected. If we assume that firm profits have a lower weight in the social welfare function than consumer utility, it is easy to see that the efficient allocation would be attained if the regulator implemented a two-part tariff. That is, the firm would receive a payment $t(K)$ per unit of capacity while having to pay a fixed amount equal to all the rents from market power. This fixed fee could then be rebated back to consumers.

In Appendix 7.2, we show that, under some reasonable conditions that allow us to do away with coordination problems that lead to a multiplicity of equilibria, the same result holds under duopoly and quantity competition.

6. CONCLUDING REMARKS

This paper proposes a simple framework to study the determinants of the investment in capacity of conventional power producers and when, under free entry and exit, there might be underinvestment from a social point of view. We focus on the presence of price caps that generate a "missing money" problem, but we show that the results extend, for example, to the case in which underinvestment occurs due to the presence of externalities. The economics literature has established that in those cases, conventional producers should receive payments set through capacity auctions designed so as to provide the right investment incentives to both incumbents and new entrants without remunerating market power.

We use this simple framework to investigate the economic impact of renewable entry into a liberalized wholesale electricity market. Renewable entry causes market prices to fall and reduces the number of hours of operation of conventional plants. The consequence is that if capacity payments are set before the potential entry of unexpected renewable capacity they will turn out to be insufficient to recover the investment costs of conventional investors, therefore, aggravating the "missing-money" problem and undermining the credibility of the capacity auction mechanism.

We interpret the findings in this paper to be in line with the conclusions presented by the European Commission in their Final Report of the Sector Inquiry on Capacity Mechanisms (European Commission, 2016). The Commission recognizes that "*Member States are concerned that existing electricity generation capacity, plus expected investment in new capacity, may be insufficient to maintain security of supply in the future,*" and accepts that, where market failures exist, incentives to invest "*may prove insufficient to maintain adequate levels of capacity in the medium and long term*."

Most importantly, the Commission explains that in order to work effectively, electricity markets depend on prices rising sufficiently in periods when supply is tight in relation to demand in times of scarcity. However, the Commission also explains that, in practice, there are multiple factors that limit the ability of producers to capture the higher scarcity prices (e.g. limited price responsive demand and regulated price caps). Further, the Commission concludes that "*market participants may still be hesitant to invest in new capacity due to considerable uncertainty about future market developments, such as the impact on their investment of the increasing market share of renewable energy and potentially extreme price volatility*."

The model presented here allows us to assess how these two market failures are related. We assess first what is the optimal capacity and capacity payment when prices are capped below the VoLL. We then assess how governments can credibly commit to maintain efficient capacity payments so that bidders in capacity auctions do not require a premium to compensate for the uncertainty.

Due to a combination of more demanding environmental objectives set by governments and a context where the cost of renewable plants falls and their efficiency increases, the entry of these plants in the market is likely to continue in the future. To restore the credibility of capacity auctions from the point of view of conventional producers, it would be enough if the government could commit to adjust capacity payments to the changes in total capacity. In this paper we have discussed two complementary mechanisms, and we have determined the suitability of each of them, depending on whether it is optimal that some conventional power plants are decommissioned or not. Both mechanisms compensate owners of power plants for their increasingly marginal use. Otherwise, it may be impossible to encourage investment in firm capacity in the future. Building a reputation of abiding previous commitments fosters participation of producers in future auctions and it implies that they will not require a premium to compensate for further changes.

Our proposal tries to shed some light on the optimal integration of renewable and conventional capacity in the electricity market, which constitutes a growing debate among regulators. Proposals like the substitution auction proposed by ISONE aim to set market mechanisms that determine the optimal capacity and how it should be distributed across tecnologies. Our paper helps in providing a benchmark for this sort of interventions.

7. APPENDIX

7.1 Proofs

Proof of Lemma 1: The characterization of K_C^* is immediate from the differentiation of the expression (3). The effect of v, c, and f can be derived using the Implicit Function Theorem. ■

Proof of Lemma 2: Similar to the proof of Lemma 1. ■

Proof of Proposition 3: This result summarizes Lemma 1 and 2. ■

Proof of Proposition 4: Using the definition of second-order stochastic dominance (see MasColell, et al. 1995),

$$\int_0^1 G(K_C+\theta\bar{K}_R)h_2(\theta)d\theta \le \int_0^1 G(K_C+\theta\bar{K}_R)h_1(\theta)d\theta$$

for any K_C. As a result,

$$\int_0^\infty (v-c)(1-G(K+\tilde{K}_R))h_2(\tilde{K}_R)d\tilde{K}_R \ge \int_0^\infty (v-c)(1-G(K+\tilde{K}_R))h_1(\tilde{K}_R)d\tilde{K}_R$$

for any K_C. Since both functions are decreasing in K_C and the optimal conventional capacity equates each of them to f, it has to be the case that $\tilde{K}_C$ is higher under $H_2(\theta)$. ■

Proof of Proposition 6: Immediate from equation (6). ■

7.2 The Duopoly Case

Consider the following duopoly version of the model discussed in section 5. There are two stages. In the first, given renewable capacity K_R, two firms, $i=1,2$, decide how much conventional capacity to build, K_C^i, at a cost per unit of f. In the second stage, given the capacity choices and the realized demand, q, each firm decides simultaneously the quantity they are willing provide to the market, $x_C^i \le K_C^i$, at a marginal cost c. To simplify the exposition, we use the tie-breaking rule that when the demand is exactly the same as the quantity provided, $K_R + x_C^1 + x_C^2 = q$, the price corresponds to $\bar{p}$.

The first result indicates that in the second stage either none of the conventional power producers sell a positive amount or the equilibrium price equals $\bar{p}$.

Lemma 7 *In the second stage, when $q < K_R$ the equilibrium price corresponds to* 0 *and $x_C^i = 0$ for $i=1,2$. Otherwise, the price is equal to $\bar{p}$ and the equilibrium quantity of firm i corresponds*

$$\tilde{x}_C^i = \min\{q - K_R - \tilde{x}_C^j, K_C^i\},$$

for $j \ne i$. In this last case, there is a multiplicity of equilibria in weakly undominated strategies and in all of them

$$\tilde{x}_C^1 + \tilde{x}_C^2 = \min\{q - K_R, K_C^1 + K_C^2\}.$$

Proof: The first part of the result is immediate since, whenever $q < K_R$, the price is lower than the marginal cost of a conventional power producer and it is optimal not to produce.

Consider now the case where $q \ge K_R$. We show that $\tilde{x}_C^1 + \tilde{x}_C^2 = q - K_R$ if $K_C^1 + K_C^2 \ge q - K_R$. Towards a contradiction suppose this is not the case. If $\tilde{x}_C^1 + \tilde{x}_C^2 < q - K_R$ at least one firm could increase its production while the price stays at $\bar{p}$. If $\tilde{x}_C^1 + \tilde{x}_C^2 > q - K_R$ the equilibrium price is lower or equal than c meaning that firms make non-positive profits and, for at least one of them, it is a weakly dominant strategy to reduce its quantity. ■

The previous proposition indicates that for any realization of demand and capacities there might be a continuum of equilibria in which total quantity stays the same but the distribution among both firms is different. Denote as $\phi(q, K_R, K_C^1, K_C^2)$ the proportion of the total demand not served by renewable sources that will be covered in equilibrium by conventional producer 1 given existing capacities and realized quantity q, $\tilde{x}_C^1 = \phi(q, K_R, K_C^1, K_C^2)(q - K_R)$.

Consider now the first stage. Suppose that firm 2 chooses a capacity K_C^2. In that case, firm 1 maximizes

$$\max_{K_C^1} \int_{K_R}^{K_R+K_C^1+K_C^2} (\overline{p}-c)\phi(q,K_R,K_C^1,K_C^2)(q-K_R)g(q)dq + (\overline{p}-c)K_C^1(1-G(K_R+K_C^1+K_C^2)) - fK_C^1$$

while a symmetric expression determines the capacity of firm 2. The next proposition characterizes the equilibrium capacity.

Proposition 8 *Suppose that the profit function of both firms is concave. In that case there is a unique subgame perfect equilibrium for a given rule* $\phi(q,K_R,K_C^1,K_C^2)$ *in which the sum of the capacity chosen by firms* 1 *and* 2 *is identical to the one a monopolist would build.*

Proof: The first-order condition that determines the capacity for firm 1 can be written as

$$(\overline{p}-c)(1-G(K_R+K_C^1+K_C^2)) + \int_{K_R}^{K_R+K_C^1+K_C^2} (\overline{p}-c)\frac{\partial\phi}{\partial K_C^1}(q-K_R)g(q)dq = f.$$

Similarly, for firm 2

$$(\overline{p}-c)(1-G(K_R+K_C^1+K_C^2)) - \int_{K_R}^{K_R+K_C^1+K_C^2} (\overline{p}-c)\frac{\partial\phi}{\partial K_C^2}(q-K_R)g(q)dq = f.$$

By concavity of the profit functions, the combination of these expressions determines uniquely the optimal capacity of each firm. Furthermore, the fact that $\tilde{x}_C^1 + \tilde{x}_C^2 = q - K_R$ whenever one firm is not selling all its capacity implies that $\frac{\partial\phi}{\partial K_C^1} = -\frac{\partial\phi}{\partial K_C^2}$. Thus, adding up both equations we have

$$(\overline{p}-c)(1-G(K_R+K_C^1+K_C^2)) = f$$

so that both firms sell together the same amount a monopolist would sell. ■

ACKNOWLEDGEMENTS

Earlier versions of this paper benefited greatly from discussions with Luis Agosti and Albert Riera. We also thank three referees for their useful comments. Financial support from the Spanish Ministry of Economics and Competitivity through grant ECO2014-57768 and Gas Natural is gratefully acknowledged. The opinions in this article are the author's sole responsibility and do not represent the views of Gas Natural or Compass Lexecon.

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