Intermittent electricity generation and investment in capacity

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Abstract

Electricity generation from intermittent sources, like wind and solar, is heavily promoted by government support schemes and by measures of dispatch priority in many countries. This paper studies strategic capacity choices between conventional dispatchable and intermittent generation technologies. We show that more intermittent capacity reduces the output level of the dispatchable firm when there is intermittent generation (strategic substitutes). However, more intermittent capacity exerts a negative externality on the firm operating the dispatchable technology: it augments the level of adequate dispatchable back-up capacity to avoid black-outs when intermittent generation conditions are unfavorable (strategic complements). We further find that, although duopoly yields lower electricity prices, an increase in intermittent capacity increases the likelihood of blackouts more under duopoly than under monopoly.

Keywords: electricity, intermittency, adequate generation capacity, oligopoly.

JEL-codes: D43, L13, Q42

1. Introduction

Increased energy capacity and electricity generation from renewable sources is high on the policy agenda in most Western countries. In 2010, renewable energy in the US accounted for 11% of total electricity generation. The Federal government and most States provide supporting schemes or portfolio standards for renewable energy. Estimates project that renewable electricity generation will increase to 15% by 2035 (IEO, 2011). Within its growth strategy, the European Union has decided that each Member country have at least 20% of its energy consumption supplied by renewable "carbon neutral" sources by 2020, and its long-term goal is to fully decarbonize its electricity sector by 2050. Some countries have already considerable shares of their electricity supplied by renewables. For example, Austria and Sweden generate 61.4% and 54.5% from renewables, mainly coming from hydropower and biomass. Germany supplies 17% of its electricity generation from renewable energy sources; this increasingly comes from wind (36%) and solar (11%), while biomass (32%) and hydropower (20%) show decreasing shares (European Commission (EC), 2012).

Governments promote the substitution of renewable energy sources (such as wind, solar, wood burning and hydro) for fossil fuels (such as coal, gases, and petroleum) for various reasons, including the fight against global warming and strategic security of energy supply.[2] Even though hydropower still constitutes the most important bulk of current renewable energy,[3] additional power comes from *intermittent* sources like wind and solar power. These are heavily promoted by many countries by a wide range of supporting schemes. For example, wind generation capacity in Europe is estimated to increase from 8% today to 16% by 2020 according to the EC's "PRIMES" model. In this paper, we focus on how the use of intermittent energy sources affects the need for total generation capacity.

The conventional way of generating electricity is mainly based on an efficient order of production to exactly meet demand at every moment. Base-load units, typically nuclear or coal-fired power plants, run at a high minimum generation level and produce at low marginal cost. Since base-load plants have slow ramp rates and are not flexible to switch on and off, they run at all times, except when they need to be maintained or a fall-out happens accidentally. More expensive flexible technologies, like gas or petrol, are dispatchable, and can take care of meeting peaks in demand or of substituting for (un)foreseen fall-outs of base-load plants. Their high ramp rates have a comparative advantage with respect to base-load plants since they are built to decrease or increase generation rapidly. The typical load-curve, therefore, shows an efficient merit-order, with base-load coming before peak-load generation, reflecting an increasing marginal cost of production.

Some of the renewable sources, like biomass and second-generation biofuels, have production characteristics that are similar to the traditional gas- or petrol-fired electricity plants. In particular, these technologies are flexible in the sense that they can be called upon when needed, show high ramp rates, and can run at low minimum generation levels. Other carbon-neutral sources, however, are typically characterized by their *intermittent* nature. Wind and photo-voltaic power -- two of the most important energy sources promoted in Europe and of growing importance in the US -- can only be called upon when there is wind or sun, respectively. Their intermittent character, however, will affect the usage of the current electricity production park significantly.[4] This holds particularly in Europe, since EU legislation in its Directive 2001/77 prescribes that wind and solar enjoy priority of dispatch.[5]

As a consequence, whenever electricity is produced by means of wind or sun, supply coming from flexible (renewable and/or non-renewable) sources must be regulated downwards to balance the system. Conversely, whenever the intermittent energy source is not available, the flexible plants are supposed to be regulated upwards to substitute for the lack of supply from the intermittent units. Moreover, dispatch priority for intermittent RES in combination with a wide range of existing support schemes (direct subsidies, feed-in tariffs or market share quotas for carbon-free energy sources) result in a higher willingness to invest in RES. However, it increases the need for adequate back-up capacity, lowers usage of existing base-load facilities[6] and, consequently, it reduces investment incentives as profitability in dispatchable capacity diminishes. This investment problem in flexible capacity is regarded by the sector players as a serious threat for the adequacy of available capacity when intermittent production units will increase their capacity share significantly in the coming future. In particular, there is ample recognition that significant levels of intermittent production will require additional generation reserve capacity.[7]

This paper studies to what extent intermittent energy sources affect the need for additional reliable, flexible power capacity if security of supply must be guaranteed. While flexible, interruptible supply contracts with plants and smart grids may partly overcome this additional need from the demand side, the issue of supply security remains when local, unexpected changes in supply force dispatchable units to be regulated almost immediately downwards or upwards. Our perspective is, therefore, not from a demand side management point of view; instead, we assume that market demand conditions are constant and market variability only comes from changes in supply conditions.

We model the electricity market in a stylized way to focus on the need for adequate capacity in a market with intermittent generation. Our basic duopoly model assumes that one producer makes use of the intermittent technology, while the other relies on conventional, dispatchable production. Both firms compete à la *Cournot* and a market-clearing spot price in the day-ahead market results. The duopoly outcomes are compared with a monopolistic market structure a single firm operates both technologies. While technical security of supply is organized differently across countries, we assume that the flexible unit must foresee sufficient reserve capacity to balance total demand absent intermittent production. In particular, when there is no wind, the flexible unit not only produces its announced quantity but also the quantity the intermittent producer would have produced if wind conditions were favorable. Moreover, we make the simplifying assumption that when there is no wind, the dispatchable firm must sell this total quantity at the market-clearing spot price that resulted from the day-ahead market.[8]

We find that output choices are *strategic substitutes* as long as the capacity constraint is not binding. However, when the capacity constraint is binding, the flexible unit must foresee sufficient capacity when the intermittent unit raises its capacity; the flexible unit must meet total demand whenever there is no intermittent production. For example, when the capacity cost for the intermittent producer decreases, it will strategically offer more capacity. The flexible producer would therefore like to reduce its capacity for the same strategic reason. However, when the capacity constraint is binding, the flexible unit must increase its capacity with respect to the capacity it would have built were the constraint not binding. In other words, when the capacity constraint is binding, the capacity choices have the characteristic of *strategic complements*. The shadow price of flexible reserve capacity is increasing in intermittent capacity. Although a duopolistic market structure implies lower electricity prices than when both flexible and intermittent capacity are operated by a monopoly, an increase in intermittent capacity raises the probability of blackouts more under duopoly.

Our paper relates to several strands of literature. Ambec and Crampes (2012) study whether a decentralized competitive market delivers the efficient mix of intermittent sources and reliable, flexible energy sources.[9] They show that with uniform pricing, wind power production is more profitable than fossil power. In particular, the uniform price is too high on windy days and too low on windless days. From an efficiency point of view, price variability should reflect the availability of intermittent energy sources, and in combination with integration of production could implement the optimal energy mix. Our approach differs from theirs since we look at strategic behavior between flexible, dispatchable and intermittent production under different market structures. Milstein and Tishler (2011) show that in a two-stage game where all firms invest in intermittent and classical dispatching generation capacity and thereafter compete à la Cournot, markets result in higher average prices and more price volatility. Twomey and Neuhoff (2010) assess the extent to which different technology owners benefit from price changes under different supply conditions. They find that, even when forward and option contracts are used, conventional generation units benefit more from market power than intermittent technologies. Our set-up clearly differs from these two papers since we do not focus on demand or supply uncertainty, while highlighting the effects of capacity investment in intermittent technologies on investment decisions for classical dispatchable generation units.

Recently, Joskow (2011) illustrates numerically why a levelized life-cycle cost[10] approach is misleading to compare the economic viability of conventional dispatchable base-load generating technologies with intermittent alternatives like wind and solar. The reason is that when intermittent sources produce less valuable electricity (windmills may spin during the night when demand is low or stand still during the day when demand is high), taking into account their lower capacity factor, their expected profitability goes down. Likewise, electricity from a solar source may be much more expensive than conventional dispatchable plants but produce more valuable electricity at noon. Relatedly, Borenstein (2012) studies the limitations of using levelized electricity generation costs to evaluate renewable energy policies. He discusses the publicly used arguments for promoting renewable energy sources and lists the externalities that appear when renewables enter the production park. Our paper stresses that even when the value of electricity is high, like solar at noon in summer, or low, at night when demand is low, the intermittent character of the source exerts a negative cost externality when this augments the need for adequate capacity.

Section 2 presents the set-up of the model. In Section 3 we discuss the main results from short-run duopolistic output choices for intermittent and conventional generation, and we analyze firms' long-run capacity choices. Section 4 provides a discussion by comparing our duopoly results with the monopoly case. We conclude and offer policy implications in Section 5.

2. Set-up of the model

We consider a duopolistic market for non-storable electricity generation. The two firms compete in a Cournot fashion and operate different technologies.[11] One firm generates electricity from a classical, flexible "dispatchable" source such as natural gas. Within the limits of the available capacity, production levels can in a flexible way be regulated upwards and downwards to serve final demand and meet all necessary network reliability conditions. The second firm generates electricity from an intermittent source like wind or solar energy. For a given capacity, realized output depends on exogenous factors, such as wind strength or sunshine, that are outside the control of the producing firm. For simplicity, we assume that there are just two states of the world. With probability $0 \leq \mu \leq 1$ there is generation (availability of wind or sun of constant strength), with probability $1-\mu$ there is no generation at all (no wind or sunshine).

Consider the intermittent electricity producer. If intermittent output is available, the output of the firm is q_I, where we assume that one unit of capacity produces one unit of output

$$q_I = K_I \,. \tag{1}$$

In this expression, K_I is the installed capacity. If the intermittent source is available, it is assumed that the variable production cost is zero.

The production process using the flexible technology is described by a standard production function that relates output, denoted q_F, to the inputs labor L and installed capacity K_F, so $q_F = f(L, K_F)$. Assuming constant input prices, we write the short-run cost function (i.e., holding installed capacity constant) associated with this production function as

$$C(q_F; K_F) \,. \tag{2}$$

The market setting is a stylized description of current practice. In practice, firms announce on the day-ahead market their production decisions for a particular short time period (e.g. for one hour, say 9am-10am) one day in advance, and they commit to delivering their announced output during that period on the next day at the price determined by the market. Consistent with this story, we assume that (i) the flexible firm announces the quantity q_F and (ii) the intermittent producer announces q_I. Both firms announce their quantities prior to the realization of the random variable, i.e., before they know whether intermittent generation will be available at the time of delivery. Consequently, the intermittent firm either generates zero or $q_I = K_I$ at the time of delivery, determined by the available capacity. The Cournot equilibrium market price $P(q_I, q_F)$ results from the total quantities offered. We further assume that if the realization of the random value is such that intermittent production is not available, the system operator enforces the flexible firm to produce and deliver the total announced quantity $q_F + q_I$. In particular, the intermittent producer buys q_I at price $P(q_I, q_F)$ from the flexible firm in the event it encounters a generation shortage at the time of delivery. As a result, our setting implies a uniform price that does not depend on whether intermittent output is available at the time of delivery: the price at which the flexible firm must sell q_I to the intermittent firm to meet total demand when the intermittent source is not available equals the prevailing price if intermittent production would have been available. Our assumption that the intermittent firm purchases power from the flexible firm at the day-ahead realized market-clearing price is specific. However, this assumption is convenient since it incorporates the need for adequate capacity requirements to meet demand at any moment in time and buys us an easy technical comparison without changing the qualitative insights of our set-up.[12]

3. Output and capacity decisions under duopoly

To fix ideas, we proceed in two separate stages. We start the analysis with the short-run output decisions, assuming installed capacities are fixed in the short-run. Next we study long-run capacity decisions.

The short-run: output and price at given capacities — Consider short-run output decisions, conditional on the installed capacities K_F and K_I. Let total market output and the resulting market clearing price be given by $q = q_I + q_F$ and $P(q)$, respectively. The composition of output depends on whether or not intermittent production will be available at the time of delivery. The inverse demand function is denoted as *P(q)*.

Under our assumptions, the flexible electricity producer maximizes

$$\underset{q_F}{\text{Max}} \quad \mu\left[P(q)\, q_F - C(q_F; K_F)\right] + (1-\mu)\left[P(q)\,(q_F + K_I) - C(q_F + K_I; K_F)\right]$$

$$\text{s.t. } q_F + K_I \le K_F \text{ and } q_F \ge 0.$$

The flexible firm maximizes its expected profit by taking into account its balancing responsibility if intermittent generation is unavailable at the time of delivery. The second constraint requires the output announced by the firm to be non-negative. Note that this will automatically be satisfied if the output of intermittent production, if available, is insufficient to satisfy total demand at the optimum; this is what we assume in what follows. The first constraint guarantees that the output to be produced, if no intermittent production is available at the time of delivery, does not exceed the firm's installed capacity.

The firm's capacity choices will guarantee that the capacity restriction is satisfied, see section 3.2 below. At an internal solution (on the possibility of a binding constraint see below) the first-order condition can be written as

$$\mu\left[(P')q_F + P - \frac{\partial C(q_F;K_F)}{\partial q_F}\right] + (1-\mu)\left[(P')(q_F+K_I) + P(q) - \frac{\partial C(q_F+K_I;K_F)}{\partial q_F}\right] = 0 \quad (3)$$

where $P' = \partial P(q)/\partial q$. This produces the optimal output $q_F(K_F, K_I, \mu)$ of the flexible producer as function of the available capacities of the two technologies and the probability of intermittent production being available at the time of delivery,.

To obtain further insight, it will be instructive to use specific functional forms for demand and costs. Let demand be linear

$$P(q) = a - bq. \quad (4)$$

The operating cost of producing electricity using the flexible technology is specified as

$$C(\tilde{q};K_F) = \tilde{q}(c - \delta K_F). \quad (5)$$

Here $\tilde{q}$ is the output to be produced using the flexible plant; depending on whether there is intermittent production, it can be either q_F or $q_F + K_I$. Our specification implies that the marginal cost of production is constant for given capacity, but declining in capacity. Moreover, the marginal effect of a capacity increase on short-run costs is negative, as it should be. We have

$$\frac{\partial C(\tilde{q};K_F)}{\partial \tilde{q}} = c - \delta K_F; \quad \frac{\partial C(\tilde{q};K_F)}{\partial K_F} = -\delta \tilde{q}.$$

Obviously, this simple specification imposes some restrictions on the parameters; for example, marginal cost of output needs to be positive, so that $\delta < c/K_F$.

Using (4) and (5), simple algebra shows that the solution to the first-order condition (3) is given by

$$q_F^* = q_F(K_F, K_I, \mu) = \frac{a - c + \delta K_F - bK_I(2-\mu)}{2b}. \qquad (6)$$

More intermittent capacity reduces the production the flexible firm will produce if there is intermittent production. But it raises the level of necessary dispatchable generation if there is no wind; indeed, using (6) we have

$$q_F^* + K_I = \frac{a - c + \delta K_F + b\mu K_I}{2b}. \qquad (7)$$

Substituting (7) in (1) gives the market price as

$$P^* = a - b(q_F^* + K_I) = \frac{a + c - \delta K_F - b\mu K_I}{2}. \qquad (8)$$

The market price declines in intermittent capacity; it also declines when the probability of intermittent production increases.

We have assumed so far that total production does not exceed capacity. A binding capacity constraint implies that at full capacity the marginal benefit of output expansion exceeds the marginal cost of doing so. The optimal output of the flexible producer then equals $K_F - K_I$. It is easy to see, using (6), that the capacity constraint will be binding if

$$K_F < \frac{a - c + \mu b K_I}{2b - \delta}. \qquad (9)$$

This expression shows that when the intermittent competitor has more capacity installed, it becomes more likely for the flexible producer that the available flexible capacity will be insufficient, so that the capacity constraint binds. This implies that intermittent production imposes an externality on flexible producers, as more flexible capacity is required to cope with unavailable intermittent production. The consequence is that more installed intermittent capacity raises the probability of a blackout, given the level of flexible capacity.

The long-run: capacity choices — In the long-run, the firms optimally adapt capacities. We assume the following quadratic capacity costs for the two firms

$$\left[r_i K_i + 0.5\eta_i (K_i)^2 \right]$$

with $i = F, I$. This implies linear marginal capacity costs for both the flexible and intermittent technology.

Consider the optimal capacity choice of the intermittent firm. This is the solution to the problem

$$\underset{K_I}{\text{Max}} \quad \mu\left[a - b\left(q_F^* + K_I\right)\right] K_I - r_I K_I - 0.5\eta_I (K_I)^2. \qquad (10)$$

Substituting the flexible output (6) and solving the first-order condition leads to the reaction function

$$K_I = \frac{\mu(a+c) - \mu\delta K_F - 2r_I}{2(\mu^2 b + \eta_I)}. \tag{11}$$

The second-order condition is easily shown to be satisfied. Observe from (11) that more flexible capacity reduces optimal intermittent capacity. A higher unit investment cost does the same. The intuition is that the marginal cost of the flexible producer decreases with its capacity K_F. Therefore, when the marginal cost of the flexible producer decreases, its strategic output level increases, so that the intermittent producer strategically decreases its capacity K_I.

Turning to the capacity decision of the flexible producer, note that optimal capacity is the solution to the problem

$$\begin{aligned}\underset{K_F}{\text{Max}}\quad & \mu\left(a - b(q_F^* + K_I) - c + \delta K_F\right)q_F^* + \\ & (1-\mu)\left(a - b(q_F^* + K_I) - c + \delta K_F\right)(q_F^* + K_I) - r_F K_F - 0.5\eta_F K_F^2 \\ & \quad \text{s.t.} \quad q_F^* + K_I \le K_F.\end{aligned}$$

Let λ be the multiplier associated with the constraint. The set of first-order conditions is

$$\begin{aligned}&\mu\left[\delta q_F^*\right] + (1-\mu)\left[\delta(q_F^* + K_I)\right] - r_F - \eta_F K_F + \lambda \le 0 \\ &\left\{\mu\left[\delta q_F^*\right] + (1-\mu)\left[\delta(q_F^* + K_I)\right] - r_F - \eta_F K_F + \lambda\right\} K_F = 0 \\ &q_F^* + K_I - K_F \le 0 \\ &\left\{q_F^* + K_I - K_F\right\}\lambda = 0.\end{aligned} \tag{12}$$

We first study the interaction between the two firms, given an internal solution to the flexible firm's capacity problem. Next we consider a binding constraint.

If the capacity restrictions does not bite, the first-order condition for optimal capacity can be written as

$$\delta q_F^* + \delta(1-\mu)K_I = r_F + \eta_F K_F. \tag{13}$$

It is easy to show that the second-order condition requires that $2b\eta_F - \delta^2$ >0. In words, the marginal capacity cost function must be sufficiently steep.

Solving the first-order condition (13) and using the output q_F^* of the flexible producer as given in (6), yields the reaction function

$$K_F = \frac{\delta(a-c) - \delta b\mu K_I - (2b)r_F}{2b\eta_F - \delta^2}. \tag{14}$$

The denominator is positive by the second-order condition, so that flexible capacity declines in both capacity cost parameters r_F, η_F. The reaction function is also downward sloping in intermittent capacity.

We can solve the reaction functions (11) and (14) for the two optimal capacities (see Appendix 1). The solutions imply

$$\frac{\partial K_F}{\partial r_F} < 0; \quad \frac{\partial K_F}{\partial r_I} > 0; \quad \frac{\partial K_I}{\partial r_I} < 0; \quad \frac{\partial K_I}{\partial r_F} > 0. \tag{15}$$

Higher capacity costs for intermittent production raise flexible capacity and reduce intermittent capacity; a similar result holds for an increase in the cost of flexible capacity.

Next, consider the outcomes in the case of a binding capacity restriction of the flexible producer. This does not change anything to the behavior of the intermittent competitor; he will react to whatever capacity the flexible producer installs according to the reaction function (11) given before. For the producer operating with the flexible technology, however, the requirement to satisfy demand has severe implications. To see this, assume that the unconstrained problem yields a solution where $q_F^* + K_I > K_F$. The flexible firm has to make sure it installs capacity that satisfies $q_F^* + K_I = K_F$; this implies, using (6), the following reaction function:

$$K_F = \frac{a - c + \mu b K_I}{2b - \delta}. \tag{16}$$

The reaction function is upward sloping. If the intermittent firm raises capacity, the flexible firm must do the same, because it knows it will have to be able to produce more when there is no intermittent production. Importantly, the inequalities shown in (15) immediately imply that the likelihood that the flexible producer faces a binding capacity constraint increases at high capacity costs for flexible capacity or when the capacity cost for the intermittent technology is low; in both cases, this will induce him to offer low capacity.

Solving the intermittent firm's reaction function (16) together with (11), we find the following (see Appendix 1):

$$\frac{\partial K_F}{\partial r_F} = 0; \quad \frac{\partial K_F}{\partial r_I} < 0; \quad \frac{\partial K_I}{\partial r_I} < 0; \quad \frac{\partial K_I}{\partial r_F} = 0. \tag{17}$$

The capacity costs of the flexible firm (η_F and r_F) play no role at all in the optimal capacities: the flexible firm has to meet the capacity restriction, no matter what its capacity cost is. Note further that a higher capacity cost for intermittent capacity now *reduces* flexible capacity. The reason is that when intermittent capacity becomes more expensive intermittent capacity declines; but this in turn makes the capacity constraint of the flexible firm less stringent, allowing it to reduce its capacity. Therefore, if the constraint binds, capacities of the two technologies are strategic complements.

The analysis is illustrated on Figures 1 and 2. First consider Figure 1. It shows the two downward-sloping reaction functions in capacities. The capacity constraint is depicted as the upward-sloping relation between the two capacities. Its intercept on the vertical axis is positive, as can be seen from (16). Any intersection of the reaction curves above or to the left of the constraint reflects an internal solution. In contrast, intersections to the right (or below) the constraint do not satisfy the capacity restriction. Now let us assume that the Nash equilibrium at the initial capacity costs (and for given values of all other parameters) is an internal solution, given by point *A*. Then, we see what happens when the cost of building flexible capacity rises, for example when there is an increase in r_F . This shifts the reaction function of the flexible producer downward, implying a new equilibrium at *B*. However, this equilibrium does not satisfy the capacity restriction since there is not sufficient flexible capacity when the conditions for intermittent production are unfavorable. Any outcome that does not satisfy the capacity restriction implies blackouts on the output market. The flexible producer is therefore forced to build more flexible capacity to satisfy the constraint. Since the flexible producer's marginal cost of production decreases with capacity, the intermittent firm strategically produces less; the resulting outcome is depicted by point *C*.

<insert Figures 1 and 2 about here>

On Figure 2, we illustrate the role of the capacity cost of the intermittent technology in a similar fashion. Starting from an internal solution at *A*, a decline in the cost of intermittent capacity leads to the unconstrained Nash equilibrium at *B*. Again, satisfying the capacity constraint requires the flexible producer to raise capacity, resulting in point *C* as the equilibrium.

The previous analysis shows that more intermittent capacity imposes a costly externality on the flexible producer by raising reserve requirements in case no intermittent generation is available. To conclude this subsection, note that this insight can also be illustrated by working out the shadow price of the capacity constraint. If the competitor installs more intermittent capacity, the shadow price of satisfying the capacity constraint for the flexible producer increases. To show this, note that (provided the capacity constraint is binding and flexible capacity is non-zero) the first-order conditions of the flexible producer's capacity choice problem boil down to

$$\begin{aligned} &\mu\left[\delta q_F^*\right]+(1-\mu)\left[\delta(q_F^*+K_I)\right]-r_F-\eta_F K_F+\lambda=0 \\ &q_F^*+K_I-K_F=0. \end{aligned} \tag{18}$$

Substituting the firm's optimal output -- as given by expression (6) -- into these conditions and totally differentiating this two-equation system yields after straightforward calculations[13]

$$\frac{d\lambda}{dK_I}=\frac{\mu\left[b\eta_F-\delta^2+b\delta\right]}{2b-\delta}>0. \tag{19}$$

This result shows that more intermittent capacity raises the shadow cost for the flexible firm of having to satisfy the capacity constraint. This reflects the cost of the responsibility for the firm to install sufficient reserve capacity that can be used if conditions for intermittent production are unfavorable.

Implications — The problem of optimal capacity choices has some simple but relevant consequences. When the cost of intermittent capacity is high relative to the capacity cost of the flexible technology, the flexible producer will provide sufficient capacity to deal with all demand, even if no intermittent production is available, and an internal solution will result. Capacities are then *strategic substitutes*. However, for sufficiently low capacity costs of the intermittent technology, the intermittent firm installs such a high level of intermittent capacity that at some point the flexible producer hits the capacity constraint. Due to the requirement of having to cover the potential unavailability of intermittent production, capacities of the two technologies become *strategic complements*. In other words, investment in wind energy capacity will raise, not reduce, the flexible (gas etc.) capacity needed to avoid black-outs.

The finding that the capacity restrictions may make intermittent and flexible capacities strategic complements has obvious policy implications. First, subsidizing intermittent capacity (reducing the firm's capacity cost) is only desirable as long as intermittent production is quite limited. With a strong and growing intermittent production sector, subsidies may have perverse effects, because they raise the probability that flexible producers have to increase capacity to meet all demand under unfavorable intermittent generation conditions (see (17)). Second, subsidies to flexible capacity have the opposite effects. When flexible capacity is abundant, such subsidies stimulate further expansion of the flexible energy sector at the expense of intermittent production. However, suppose that the cost of flexible capacity is large relative to that of intermittent investment (one then expects the sector of intermittent production not to be very small). Subsidies to flexible capacity will then relax the capacity constraint of flexible producers, and compensate them for the requirement imposed on them.

We summarize the main insights in the following Proposition.

Proposition 1. Capacity choices under duopoly.

a. **The requirement imposed on the flexible producer to install sufficient capacity to cope with the absence of intermittent generation implies that flexible and intermittent capacity may become strategic complements.**
b. **The shadow price of the constraint on reserve capacity is increasing in intermittent capacity.**
c. **Subsidies to intermittent capacity may have perverse effects, as they may require additional capacity investment by flexible producers.**

4. Discussion

In this section, we offer a brief comparison with a monopolistic producer that jointly operates the flexible and intermittent technology. The monopoly case is interesting because it not only raises the market power of the firm (as compared to the flexible producer under duopoly), but the availability of the extra technology may allow the monopolist to internalize the externality identified in the previous section.

The monopoly case — If intermittent production is available, the firm produces $q_I = K_I$ using the intermittent technology and the remaining $q_F = q - K_I$ is produced by its flexible technology. The market price is determined by total output $q_F + K_I$. We formulate the firm's problem of short-run expected profit maximization, for given installed capacities, as

$$\underset{q_F}{\text{Max}} \;\; P(q_F + K_I)(q_F + K_I) - \mu C(q_F; K_F) - (1-\mu) C(q_F + K_I; K_F)$$
$$\text{s.t.} \quad q_F + K_I \le K_F$$
$$q_F \ge 0.$$

The interpretation of the constraints was discussed in the previous section. As before, we assume that intermittent production, if available, is insufficient to satisfy total demand, so that the second restriction is satisfied at the optimum.

The first constraint may be binding at the optimum if at full capacity the marginal benefit exceeds the expected marginal cost. However, in what follows we focus on an internal solution. Associating a Lagrange multiplier λ with the capacity constraint, the first-order condition is

$$(P')(q_F + K_I) + P - \mu \frac{\partial C(q_F; K_F)}{\partial q_F} - (1-\mu) \frac{\partial C(q_F + K_I; K_F)}{\partial q_F} = 0 \tag{20}$$

This expression equates marginal revenue and expected marginal cost; the latter depends on the availability of intermittent output.

Using the demand and cost specifications (4)-(5) suggested before, we can solve the first-order condition to find

$$q_F^M = \frac{a - c + \delta K_F - 2bK_I}{2b}. \tag{21}$$

The superscript '*M*' refers to the monopoly outcome. Total market production is

$$q_F^M + K_I = \frac{a - c + \delta K_F}{2b}. \tag{22}$$

Price is given as

$$P^M = a - b(q_F^M + K_I) = \frac{a + c - \delta K_F}{2}. \tag{23}$$

Note that output, and therefore price, are independent of both the probability of availability of intermittent output and the capacity of the intermittent technology installed. This is due to our assumption that marginal operating cost does not increase if the flexible technology has to produce a higher output level when no intermittent output is available.[14] More available intermittent capacity reduces optimal output q_F on a one-to-one basis, more flexible capacity raises output. The impact of the cost and demand parameters is as expected. Of course, if the capacity constraint is binding, output and price are simply given as

$$q_F^M = K_F + K_I; \quad P^M = a - bK_F.$$

Given the above expressions, this will be the case if for the initial flexible capacity installed the following holds

$$K_F^M < \frac{a-c}{2b-\delta}. \tag{24}$$

Note that this can only be the case at positive flexible capacity if $2b-\delta>0$. A binding constraint is more likely to occur when the market potential is high (a) or at low marginal production cost (c).

Next turn to the monopolist's capacity choices. Observe that it may be optimal not to build any intermittent capacity at all; straightforward analysis shows that this can be the case if the probability of intermittent production is very small and/or if intermittent capacity costs are large. Not building flexible capacity can never be optimal, because the firm is responsible for delivering output demanded even if no intermittent production is available.

Consider an internal solution where the capacity constraint is not binding. Using (4)-(5) in the first-order condition for the firm's output choice (20), simple algebra shows that the first-order conditions for optimal capacities can be written as

$$\mu\delta q_F^M + (1-\mu)\delta(q_F^M + K_I) - r_F - \eta_F K_F = 0 \tag{25}$$

$$a - 2b(q_F^M + K_I) - (1-\mu)(c - \delta q_F^M) - r_F - \eta_F K_F = 0. \tag{26}$$

These expressions just set the marginal costs and benefits of capacity investment equal. To understand the last expression, note that more wind energy capacity raises wind energy output only if there is wind; this occurs with probability μ. This saves the firm the marginal cost of having to produce this additional output using gas turbines.

Expressions (25)-(26) can be rearranged so that

$$K_F^M = \frac{\delta(a-c) - 2\delta b\mu K_I^M - 2br_F}{2b\eta_F - \delta^2} \tag{27}$$

$$K_I^M = \frac{\mu c - r_I - \mu\delta K_F^M}{\eta_I}. \tag{28}$$

Note that second-order conditions require

$$\delta^2 - 2b\eta_F < 0; -\eta_I < 0; (2b\eta_F - \delta^2)\eta_I - 2b\mu^2\delta^2 > 0.$$

Solving (27)-(28) for the two optimal capacities as functions of the parameters gives fairly complex analytic solutions that do not give much direct insight. However, it does easily follow that they imply

$$\frac{\partial K_F^M}{\partial r_F} < 0; \quad \frac{\partial K_F^M}{\partial r_I} > 0; \quad \frac{\partial K_I^M}{\partial r_I} < 0; \quad \frac{\partial K_I^M}{\partial r_F} > 0. \tag{29}$$

As expected, the two technologies are substitutes. A higher capacity cost for a given technology reduces its optimal capacity and raises optimal capacity of the other.

Finally, let us assume that the capacity restriction $q_F^M + K_I \leq K_F$ is binding at the optimum. Using earlier results (see (22)), this happens when at the optimal capacity choice the following holds:

$$\frac{a - c + \delta K_F^M}{2b} > K_F^M \tag{30}$$

or, equivalently, $K_F^M < (a-c)/(2b-\delta)$. This condition is more likely to be satisfied when flexible capacity costs are high and intermittent capacity costs are low.

Substituting the capacity constraint into the objective function and reconsidering the choice of optimal capacities, we can rearrange the first-order conditions and have:

$$K_F^{M'} = \frac{a - c - \mu\delta K_I - r_F}{2(b+\delta) + \eta_F} \tag{31}$$

$$K_I^{M'} = \frac{\mu c - r_I - \mu\delta K_F}{\eta_I}. \tag{32}$$

Solving for the two capacities, we find that the effects of capacity costs on optimal capacities have the same signs as in (29) above. In other words, the capacity constraint leads the firm to adjust its joint capacity choices, but it does not affect the direction in which it adjusts capacities when capacity costs change.

Comparison between duopoly and monopoly — What are the implications of comparing the results under monopoly and duopoly? First, as expected, comparing (21)-(23) with (6)-(8), we see that as long as intermittent capacity is not zero, the price will be lower under duopoly, with higher output provided. This has a simple policy implication: taking a situation without intermittent capacity as starting point, it suggests that having a new competing firm introduce intermittent capacity (implying a duopolistic market structure) results in lower prices and higher output on the electricity market than when the flexible producer himself initiates intermittent production. Second, based on the same comparison, both a higher probability of intermittent production and more intermittent capacity yield higher output and lower prices under duopoly. Under monopoly, however, price and total output are independent of these parameters. Third, from (16) and (24) it follows that under duopolistic competition, the available capacity of the flexible technology is more likely to be insufficient to satisfy demand (hence, to lead to blackouts) when more intermittent capacity is installed. Fourth, by comparing the internal solutions (14) and (27) we find that, conditional on a given intermittent capacity, a monopolist will offer less flexible capacity than under duopoly.

Finally, when a monopolist operates the two generation technologies, both capacities can always be considered substitutes. This was not necessarily the case under duopoly. When the cost of intermittent capacity is high relative to the capacity cost of the flexible technology, the flexible producer will provide sufficient capacity to deal with all demand, even if no intermittent production is available, and an internal solution will result. Capacities are then strategic substitutes. However, for low costs of intermittent capacity, the flexible producer may hit the capacity constraint and is forced to install more flexible capacity in response high levels of installed intermittent capacity. Then the two technologies become strategic complements. In other words, investment in wind energy capacity will raise, not reduce, the flexible (gas etc.) capacity needed to avoid black-outs.

We summarize the main insights from this section in the following Proposition.

Proposition 2. Comparing monopoly and duopoly

a. **Electricity prices will be lower when the intermittent technology is operated by a competing firm than when it is operated by the flexible producer.**
b. **An increase in intermittent capacity raises the probability of a blackout more under duopoly than under monopoly.**
c. **Under monopoly, the flexible and intermittent technology are always strategic substitutes. Duopoly implies that at low costs of intermittent capacity the two technologies become complements.**

5. Conclusions

The introduction of renewable energy sources is perceived by different stakeholders as an important step towards the decarbonization of electricity sectors in many countries. The wide range of supporting schemes for renewable energy sources, combined with the pricing of emissions for conventional carbon-based power plants results already now in significant generation shares coming from renewable energy sources. By 2050, the European Union wants to fully decarbonize its electricity sector. Of high importance is the growing reliance on intermittent energy sources like wind and sunshine. While such an increasing reliance on intermittent carbon-free energy sources certainly contributes to the policy goal of responding to changes in climate, the need for adequate supply of power may at the same time become more urgent.

This paper stresses that, indeed, more intermittent capacity reduces the production level of dispatchable flexible plants when the conditions for intermittent generation are favorable. Insofar as these intermittent units substitute for carbon-based units like natural gas-fired plants, the goal to generate more power from carbon-free sources will be reached. However, a significant level of intermittent capacity raises at the same time the need for more flexible capacity to generate adequate production levels when intermittent generation conditions are unfavorable. In other words, instant availability of more flexible power resources will become more urgent as the share of intermittent capacity grows.

One way to meet this requirement is to build more flexible plants. It is, however, unclear to what extent investors will be willing to build new plants when their usage will be unpredictable or at too low a level. One alternative to this is to augment the interconnection of power markets to increase the availability of existing plants. Within the context of the European Union, more market integration may contribute to this challenge. Availability, however, will strongly depend, among others, on the correlation between the needs for adequate supply across markets. Either way, as intermittent capacity grows, infrastructure to provide adequate back-up capacity will be needed to meet final demand when the consequences for adequate supply under unfavorable conditions for intermittent generation are significant.

Appendix 1: capacity choices

We solve (11)-(14) by Cramer's rule. We find:

$$K_F = \frac{\left[\mu^2\delta b(a-3c)+2\eta_I a\right]-\left[4b(\mu^2 b+\eta_I)\right]r_F+(2b\mu\delta)r_I}{b\mu^2(4b\eta_F-\delta^2)+2\left(2b\eta_F-\delta^2\right)\eta_I}$$

$$K_I = \frac{\left[2\mu(b\eta_F-\delta^2)\right]a+\left(2\mu b\eta_F\right)c-\left[2\left(2b\eta_F-\delta^2\right)\right]r_I+(2b\mu\delta)r_F}{b\mu^2(4b\eta_F-\delta^2)+2\left(2b\eta_F-\delta^2\right)\eta_I}.$$

In the case of a binding capacity constraint, we solving the intermittent firm's reaction function (16) together with (11). We find:

$$K_F = \frac{\left[\mu^2 b(3a-c)+2(a-c)\eta_I\right]-(2\mu b)r_I}{2(2b-\delta)(\mu^2 b+\eta_I)+\mu^2 b\delta} \text{ and } K_I = \frac{2\mu\left[b(a+c)-\delta a\right]-2(2b-\delta)r_I}{2(2b-\delta)(\mu^2 b+\eta_I)+\mu^2 b\delta}.$$

Figure 1: an increase in the investment cost of flexible capacity.

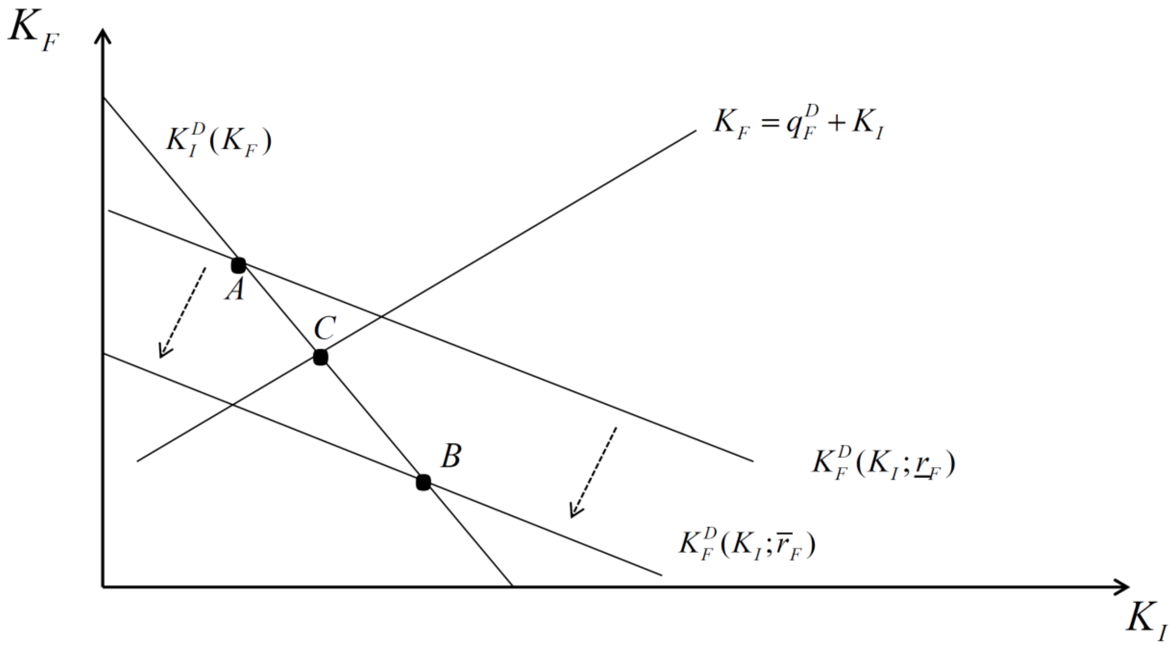
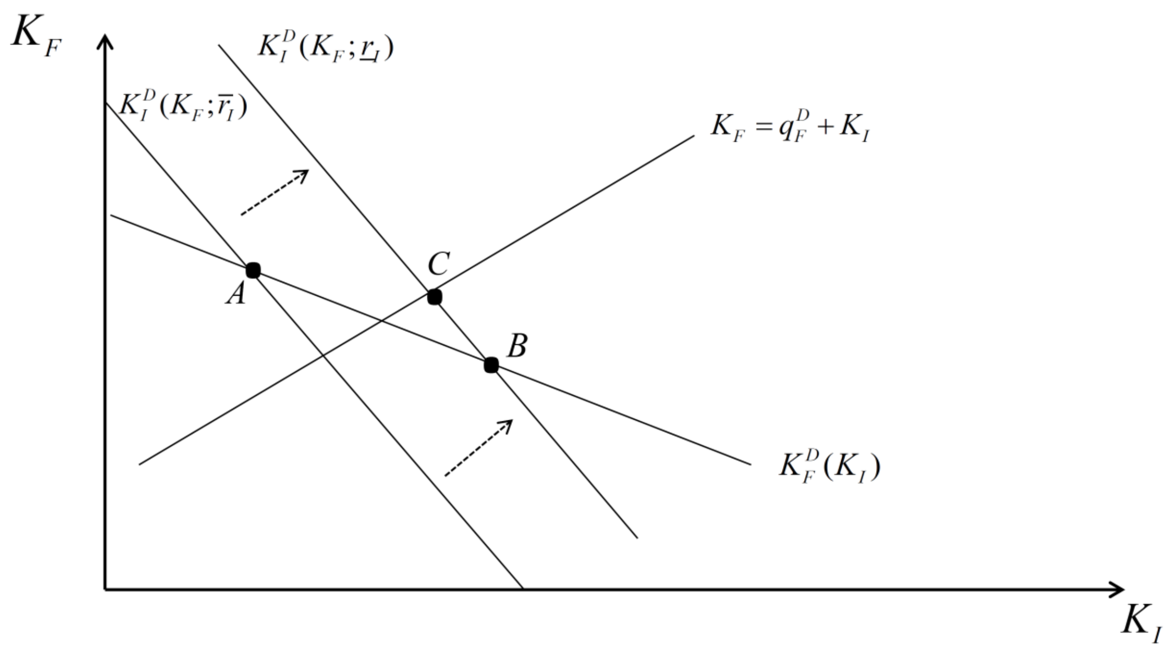


Figure 2: a decrease in the investment cost of intermittent capacity.



References

Ambec, Stefan and Claude Crampes, 2012, Electricity provision with intermittent sources of energy, *Resource and Energy Economics*, 34, 319-336.

Boccard, Nicolas, 2009, Capacity factor of wind power realized vs. estimates, *Energy Policy*, 37, 2679-2688.

Borenstein, Severin, 2012,The Private and Public Economics of Renewable Electricity Generation, *Journal of Economic Perspectives*, 26, 1, 67-92.

Borenstein, Severin, Bushnell, James and Steven Stoft, 2000, The competitive effects of transmission capacity in a deregulated electricity industry, *RAND Journal of Economics*, 31, 2, 294-325.

Congressional Research Service, 2011, U.S. Renewable Electricity Generation: Resources and Challenges, 7-5700 R41954.

Eurelectric, 2010, Integrating intermittent renewable sources into the EU electricity system by 2020: Challenges and Solutions.

European Commission, 2012, Consultation Paper on generation adequacy, capacity mechanisms and the internal market in electricity.

European Commission, 2012, EU energy in figures, statistical pocket book, ISSN-1977-4559.

International Energy Outlook, 2011, www.eia.gov/ieo/pdf/0484(2011).pdf.

Green, Richard and Nicholas Vasilakos, 2010, Market behaviour with large amounts of intermittent generation, *Energy Policy*, 38, 3211-3220.

Green Richard and Nicholas Vasilakos, 2011, The Long-term Impact of Wind Power on Electricity Prices and Generating Capacity, General Meeting of the IEEE-Power-and-Energy-Society (PES), IEEE.

Joskow, Paul, 2011, Comparing the costs of intermittent and dispatchable electricity generating technologies, *American Economic Review*, 101,3, 238-241.

Ketterer, Janina, 2012, The Impact of Wind Power Generation on the Electricity Price in Germany, Ifo WP-143.

Milstein, I, and A. Tishler, 2011, Intermittently renewable energy, optimal capacity mix and prices in a deregulated electricity market, *Energy Policy* 39 (2011) 3922–3927.

New York Independent System Operator, 2010, "Growing wind: final report of the NYISO 2010 wind generation study", www.nyiso.com .

Rupérez Micola, Augusto and Albert Banal-Estanol, 2011, Production intermittence in spot markets, LSF Working Paper Series, Université de Luxembourg.

Twomey, Paul and Karsten Neuhoff, 2010, Wind power and market power in competitive markets, *Energy Policy*, 38, 3198-3210.

Willems, Bert, Rumiantseva Ina, Weigt Hannes, 2009, Cournot versus Supply Functions: What does the data tell us?, *Energy Economics*, 31, 38-47.

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[2] The creation of a single EU-market for energy as another specific goal within Europe.

[3] For the US, in 2010, the share of hydropower was 7%, while the remaining 4% came from other sources like wind, solar, and biofuels. In the European Union, the capacity share of hydro was 14% whereas capacity shares for wind and solar represented 11% and 7%, respectively.

[4] See e.g. Borenstein (2008) for an extensive cost-benefit study on solar PV.

[5] "When dispatching generating installations, transmission system operators shall give priority to generating installations using renewable energy sources insofar as the operation of the national electricity system permits." EC Directive 2001/77 Article 7 §1.

[6] For example, CCGT plants in Spain were only half as much dispatched at full capacity in between 2004 and 2010 (Eurelectric, p.10, Figure 2).

[7] The NYISO concludes in its 2010 report on p.45: "[T]he reserve margin requirement will increase as the penetration of wind resource increases because wind has a lower availability relative to other resources and its unavailability is highly correlated." On p. v: "[T]he addition of 1 MW of wind would allow approximately 0.2 MW to 0.3 MW of existing resources to be removed in order to still meet the resource adequacy criteria. The balance of the conventional generation must remain in service to be available for those times when the wind plants are unavailable because of wind conditions and to support larger magnitude ramp events." On p.99: "[T]his study shows the feasibility of maintaining reliable electric service with the expected level of intermittent renewable resources associated with the current 20% RPS, provided that existing generation remains available to provide back-up generation and essential reliability services."

[8] For example, in Europe, most countries require that the grid operator buys the in-feed of renewable energy according to a pre-specified price schedule (e.g. a "feed-in tariff"). However, there is no obligation from the side of the intermittent producers to deliver when weather conditions are unfavorable (or more favorable than expected). In that event, the grid operator must take care of the stability of the system and buy from conventional units if expected generation from intermittent sources was too high (or sell on the market when expectations were too low). We assume, for simplicity, that the price the grid operator must pay equals the market-clearing price resulting from favorable wind conditions. In other countries, like Germany, intermittent generators have already some choice between a pre-determined feed-in tariff and selling directly on the spot or forward market. Price volatility effects from intermittent generation are very important, as empirically shown by Green and Vasilakos (2010, 2011) and Ketterer (2012). In this paper, however, we abstract from price volatility to focus on strategic capacity choices only.

[9] In a different setting, Rupérez Micola and Banal-Estanol (2011) simulate the effects of intermittent production on volatility of spot prices.

[10] Intermittent sources typically perform much better than conventional dispatchable sources in terms of fixed cost (price/MW) and in terms of operating costs (price/MWh). However, their capacity factor (i.e. the ratio between actual output for a given time period and full nameplate capacity) is significantly lower. For example, Boccard (2009) finds that the average capacity factor for wind is below 21% in Europe and around 25-30% in the US, whereas for photo-voltaic solar energy, the literature finds that the capacity factor varies between 15-

20% (Joskow, 2011). In contrast, conventional resources like base-load nuclear units or flexible gas plants, generally have a higher availability in between 85-90% (NYISO, 2010).

[11] As in Borenstein et al. (2000), we make use of a Cournot framework. Although the Cournot set-up is highly stylized and different as a description from e.g. the supply function equilibrium approach where firms announce quantities and prices, our framework simplifies the analysis while safeguarding our purposes.

[12] To see this, suppose several flexible firms offer power to the intermittent unit on a competitive basis. This set-up would of course result in a difference between the market clearing price on the day-ahead market and the intra-day or balancing market. In particular, take the reasonable assumption that the (expected) price is higher than the day-ahead market. This would clearly reduce the profitability of the intermittent firm and potentially increase the flexible firms' profits. However, the main insights derived on this paper would not be qualitatively affected.

[13] Note that $(b\eta_F - \delta^2) > 0$, see before. Moreover, if $(2b - \delta) > 0$ does not hold then the capacity constraint can never be binding, see (9).

[14] It is straightforward to allow increasing marginal production cost. This clearly shows the role of the increase in cost on the market price when no intermittent output is available. However, it does not affect the qualitative conclusions from the model and substantially complicates the capacity choice problem studied below.