Intermittent electricity generation and investment in capacity

Jan Bouckaert and Bruno De Borger[1]

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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 generation level of the dispatchable firm when there is intermittent generation (strategic substitutes). However, more intermittent capacity exerts a negative externality as it augments the level of adequate dispatchable back-up capacity to avoid black-outs when intermittent generation conditions are unfavorable (strategic complements).

[1] Department of Economics, University of Antwerp, Prinsstraat 13, B-2000 Antwerp. jan.bouckaert@ua.ac.be; bruno.deborger@ua.ac.be . We thank Walter Nonneman and Thomas Peeters for comments.

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.[2] 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 to fully decarbonize its electricity sector by 2050. Although large differences still occur between its Member countries 2010 figures show that Europe produces almost one fifth of its electricity from renewable energy sources. Some countries have already considerable shares of their electricity supplied by renewables. Austria generated 61.4% from renewables whereas Sweden had 54.5% of renewable energy supply. In both countries, this mainly comes from hydropower and biomass. Germany supplied already 17% of all its electricity generation from renewable energy sources (European Commission (EC), 2012). However, this share increasingly comes from wind (36%) and solar (11%) while biomass (32%), hydro (20%) show decreasing shares.

There are several reasons why 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. One important reason is the fight against global warming, while another is the strategic security of energy supply.[3] While hydropower still constitutes the most important bulk of current renewable energy,[4] additional power mainly comes from intermittent sources like wind and solar power, and are heavily promoted by numerous countries. 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. These additional renewable power sources are heavily supported by a wide range of supporting schemes. A change towards more use of these renewable energy sources with an intermittent production characteristic will, however,

[2] See www.dsireusa.org for an overview of initiatives at the Federal level and across all States.
[3] The creation of a single EU-market for energy as another specific goal within Europe.
[4] 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.

significantly alter the organization of generation and transmission. 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. First, 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. Second, more expensive, flexible technologies, like gas or petrol, are dispatchable, and take care of meeting peaks in the demand or substitute 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.

Since demand and supply of electricity must be in equilibrium at any moment in time to avoid black-outs, sufficient availability at all times is key to the organization of an efficient production portfolio. This requires reliable and adequate capacity. System reliability secures against technical disturbances, like short-circuits or accidental short-term plant fall-outs that must be solved instantaneously by making use of short-term reserve capacity. The capability of the system to meet demand at all times requires adequacy of the available capacity. Adequacy of capacity can be divided into long-term capacity to meet peak moments and back-up capacity to respond to expected long-term fall-outs.

The redirection from fossil-based burning and nuclear towards more renewable energy sources (RES) will imply drastic challenges for the reliability and adequacy of the system. Since smart-grid technology is not yet sufficiently developed or still too expensive, little help from the demand side should be expected in the short run. As a consequence, the supply side of the market, i.e. the transmission operators and generators, will be needed to adjust to the changes in the generation characteristics to meet demand.

Some of these RES, like biomass and second-generation biofuels, have production characteristics that are identical 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 (PV) power, two of the most important promoted RES 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.[5] This holds particularly in Europe, since EU legislation in its Directive 2001/77 prescribes that wind and PV enjoy priority of dispatch.[6]

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[7] and consequently, 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.[8]

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

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

[6] "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.

[7] For example, CCGT plants in Spain were only half as much dispatched at full capacity in between 2004 and 2010 (Eurelectric, p.7, in Red Electrica España).

[8] 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."

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, so that we assume that market demand conditions are constant and market variability only comes from changes in supply conditions.

We model the interaction between intermittent and flexible production for a monopoly and a duopoly. Under monopoly, the profit-maximizing capacity choice between intermittent and conventional dispatchable production is fully internalized. We show that both technologies are substitutes, i.e. a higher capacity cost for a given technology reduces its optimal capacity and raises the optimal capacity of the other technology. In addition, when the capacity becomes a binding constraint, a change in capacity costs results in a joint adjustment of capacities.

Under duopoly, we model the electricity market in a stylized way while maintaining the essential characteristics for the purposes of our study. In particular, we assume 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. 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.[9] We find that, as under monopoly, 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

[9] 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.

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*.

Our paper relates to the following literature. 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.

Ambec and Crampes (2012) study whether a decentralized competitive market delivers the efficient mix of intermittent sources and reliable, flexible energy sources.[11] 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

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

optimal energy mix. Our approach differs from theirs since we look at strategic behavior between flexible, dispatchable and intermittent production under different market structures.

Section 2 presents the set-up of the model. Section 3 discusses the short-run output choices for intermittent and conventional production for monopoly and duopoly. Section 4 presents the long-run capacity choices for both market structures. We conclude in Section 5.

2. Structure of the model

We consider a market for non-storable electricity generation where two technologies are available. The first technology is based on a classical "dispatchable" (non-renewable) 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 technology is an intermittent source such as wind or solar energy. For a given capacity, realized output depends on exogenous factors, such as wind strength and sunshine, that are uncontrollable by the producing firm. Throughout the analysis we will refer to these two technologies as flexible and intermittent energy production. We denote the installed capacity for the production of electricity using flexible and intermittent technologies by K_F and K_I, respectively.

We first consider intermittent production. For simplicity, we assume that there are just two states of the world. With a probability $0 \leq \mu \leq 1$ there is intermittent production (availability of wind or sun of constant strength), with the remaining probability $1-\mu$ there is no production at all. In the former case, we denote the intermittent output by q_I, where we assume that one unit of capacity produces one unit of output

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

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 associated with this production function as

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

The notation ";" is used to indicate that variables after this symbol are treated as exogenously given by the firm in the short-run. In the long-run, capacity is a policy variable the firm can optimally choose.

In the remainder of this paper, we first assume that both technologies are operated by a single monopolist. Next we analyze the case where the flexible and intermittent producers are duopolists, competing in a Cournot fashion. The purpose of the analysis is to compare price, output and capacity decisions under the two market structures.

The market setting is a stylized description of current practice. In practice, firms announce 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 output at the price determined by the market. Consistent with this story, we assume that the firm operating the flexible technology announces the quantity it offers prior to the realization of the random variable, i.e., before it knows whether intermittent production will be available at the time of delivery. Specifically, the intermittent producer either delivers zero at the time of delivery, or a given quantity $q_I = K_I$ determined by the available capacity. The flexible producer announces the quantity q_F. Both under monopoly and duopoly, we further assume that if the realization of the random value is such that intermittent production is not available, the firm owning the flexible technology commits to produce and deliver the total quantity $q_F + K_I$. In other words, if needed the flexible firm is responsible for delivering the unavailable intermittent output. Under duopoly, this therefore implies that the flexible producer is responsible for unavailable production by his competitor. Finally, we assume that the market clearing price results in a Cournot fashion from the total quantity offered. Although highly stylized and different as a description from the supply function equilibrium approach where firms announce quantities and prices, the Cournot framework finds empirical support for our purposes.[12]

Note that 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 to meet total demand when power from the intermittent source is not available

[12] As in Borenstein et al. (2000), we make use of a Cournot framework. See also Willems et al. (2009) who empirically find support that the Cournot framework, as an alternative to the supply function framework, is a reasonable approach to model a wholesale market.

equals the prevailing price when intermittent production would have been available. One interpretation is that both the flexible and the intermittent producer announce their quantities in advance; the latter just announces $q_I = K_I$. But assume the intermittent firm then has the right to buy its earlier announced intermittent quantity from the flexible technology at the earlier realized market-clearing price in the event the realization of the random variable is unfavorable.[13] This assumption approaches the "reserve requirements" contracts at a pre-specified price that system grid operators write with flexible generators when an outage or an unforeseen spike in demand occurs. While the assumption of buying at the earlier realized market-clearing price is a specific one, it is helpful as it buys us an easy technical comparison without changing the qualitative insights of our set-up. Finally, this assumption takes the need for adequate capacity requirements into account in our model.

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

3. Output decisions in the short-run: monopoly versus duopoly

We consecutively look at the outcomes under monopoly and duopoly, and then draw some conclusions based on a brief comparison.

3.1. Output choices under monopoly

We first consider the problem for a monopolist that has to decide on the output he will announce on the market, given the installed capacities of the two technologies K_F, K_I he has available. The composition of output depends on whether or not intermittent production will be available at the time of delivery tomorrow. We denote total market output by *q*; the price is denoted by *P*.

First, 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

[13] Alternatively, the Transmission System Operator (TSO) buys the quantity announced by the intermittent producer from the dispatchable generation unit. .

(say, gas turbines). The market price is determined by total output $q_F + K_I$. Operating profit (net of fixed costs, which are constant in the short-run) can in that case be written as

$$P(q_F + K_I)*(q_F + K_I) - C(q_F; K_F)$$

where *P(.)* is the inverse market demand function. Revenues are generated on the total output produced but, since conditional on capacity the operating cost of intermittent production is zero, the firm only incurs production costs for production based on the flexible technology.

Second, if there turns out to be no intermittent production, then the firm has to produce the full quantity demanded using its flexible technology. Production by the flexible technology, and hence, production costs, now include output K_I not delivered by the intermittent technology. Profit is therefore

$$P(q_F + K_I)*(q_F + K_I) - C(q_F + K_I; K_F).$$

Before proceeding, note the interpretation of q_F: it is the output produced by the flexible technology in case intermittent production is available. We can then formulate the firm's problem of short-run expected profit maximization as

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

The first constraint says that the flexible capacity installed must allow to deliver total production, independent of whether or not intermittent production will be available. The second constraint restricts flexible production in the presence of intermittent output to be nonnegative. This second constraint will be irrelevant if we assume that intermittent production, if available, is insufficient to satisfy total demand. This is what we assume in what follows, so the second restriction is assumed to be satisfied at the optimum.

Associating a Lagrange multiplier λ with the capacity constraint, the first-order conditions are

$$\begin{aligned} &(P')(q_F + K_I) + P - \mu \frac{\partial C(q_F; K_F)}{\partial q_F} - (1-\mu) \frac{\partial C(q_F + K_I; K_F)}{\partial q_F} - \lambda = 0 \\ &q_F + K_I \le K_F \\ &\left[q_F + K_I - K_F \right] \lambda = 0, \end{aligned}$$

where $P' = \dfrac{\partial P(q_F + K_I)}{\partial q_F}$.

Of course, the firm may decide to produce up to capacity, or if flexible capacity is currently small, it may have to produce up to capacity; in both cases, the capacity constraint is binding. The optimum is then given as $q_F = K_F - K_I$, and more intermittent capacity implies that the firm, if intermittent production is available, is forced to produce less output based on the flexible technology. A binding constraint may be optimal if at full capacity the marginal benefit exceeds the expected marginal cost. Indeed, the set of first-order conditions show that a binding capacity restriction implies

$$(P')(q_F + K_I) + P > \mu \frac{\partial C(q_F; K_F)}{\partial q_F} + (1-\mu)\frac{\partial C(q_F + K_I; K_F)}{\partial q_F}$$

Let is now focus on an internal solution. We then have

$$(P')(q_F + K_I) + P - \mu \frac{\partial C(q_F; K_F)}{\partial q_F} - (1-\mu)\frac{\partial C(q_F + K_I; K_F)}{\partial q_F} = 0 \qquad (3)$$

This expression equates marginal revenue and expected marginal cost; the latter depends on the availability of intermittent output. The solution to the first-order condition gives optimal flexible output when intermittent output is available as a function of exogenous parameters and the available capacities; for later reference, we can write $q_F = q_F(K_F, K_I, \mu)$.

We are interested in the effect of exogenous parameters (such as the wind probability) and of variables that are fixed in the short-run (capacities) on the firm's optimal output and price decisions. Although this can be done in general, to study such effects and get transparent results it seems instructive to specify functional forms for demand and cost functions. Let demand be linear

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

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

$$C(q; K_F) = q(c - \delta K_F). \qquad (5)$$

Here 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 $q_F + K_I$. This 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

$$\frac{\partial C(q;K_F)}{\partial q} = c - \delta K_F; \quad \frac{\partial C(q;K_F)}{\partial K_F} = -\delta q. \tag{6}$$

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 these specifications, we can solve the first-order condition (3) to find

$$q_F^M = \frac{a - c + \delta K_F - 2bK_I}{2b}. \tag{7}$$

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

$$q_F^M + K_I = \frac{a - c + \delta K_F}{2b}. \tag{8}$$

Price is given as

$$P^M = a - b(q_F^M + K_I) = \frac{a + c - \delta K_F}{2}. \tag{9}$$

Note that output, and therefore price, are independent of both the probability of there being intermittent output and of the capacity of the intermittent technology installed. This is due to our strong 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

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

[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.

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).

3.2. Output choices under duopoly

Let us now turn to production decision when the flexible and intermittent technology are operated by separate firms, competing in a Cournot fashion. However, unlike in a standard Cournot setting, the flexible producer is required to make up for the absence of intermittent production, if this turns out to be the case. He will therefore incorporate this possibility into his output decisions.

Suppose first that the flexible firm has enough capacity available to cope with all demand, even if there is no intermittent production, so we have an internal solution. At the output choice stage, we can then solve the problem ignoring the constraint on capacity. The problem of the flexible firm is

$$\max_{q_F} \mu\left[a - b(q_F + K_I) - c + \delta K_F\right] q_F + \\ (1-\mu)\left[a - b(q_F + K_I) - c + \delta K_F\right](q_F + K_I).$$

The solution for output

$$q_F^D = \frac{a - c + \delta K_F - bK_I(2-\mu)}{2b}. \tag{10}$$

where the superscript 'D' refers to the duopoly solution.

More intermittent capacity reduces the production q_F the flexible firm will produce if there is intermittent production. But it raises the level of necessary dispatchable generation if there is no wind, because

$$q_F^D + K_I = \frac{a - c + \delta K_F + b\mu K_I}{2b}. \tag{11}$$

This gives the market price as

$$P^D = a - b(q_F^D + K_I) = \frac{a + c - \delta K_F - b\mu K_I}{2}. \qquad (12)$$

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

We have assumed here that this total production level does not exceed capacity. The capacity constraint will be binding if

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

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 is not surprising since more intermittent capacity implies that more flexible capacity is required to cope with unavailable intermittent production. This effect is absent for the monopolist y, because his intermittent capacity does not affect its total output level, as analyzed in Section 3.1.

3.3. Output choices under monopoly and duopoly: Implications

The above analysis has a number of relevant implications. First, as expected, comparing (8)-(9) with (11)-(12), we see that as long as intermittent capacity is not zero, the price will be lower under duopoly, with higher output provided. Second, based on the same comparison, the probability of wind and intermittent capacity yield higher output and lower prices under duopoly but, under monopoly, price and total output are independent of intermittent capacity and probability of intermittent production. Third, suppose we start hypothetically from a situation without intermittent capacity. Then the above analysis yields an important policy conclusion: it shows that having intermittent capacity being introduced via a competing firm (implying a duopoly) results in lower prices and higher output on the electricity market than when the flexible producer initiates intermittent production. Finally, under duopolistic competition, the available capacity of the flexible technology is more likely to be insufficient to satisfy demand when more intermittent capacity is installed.

We summarize the most important insights from this section in the following Proposition.

Proposition 1. Output choices for given capacities.

a. **Prices are lower under duopoly than under monopolistic energy provision.**

b. **A higher probability of intermittent production and an increase in the intermittent capacity installed raise output and reduce price only under duopolistic competition. In a duopoly more installed intermittent capacity raises the probability of a blackout given the level of flexible capacity.**

4. The long-run: capacity choices under monopoly and duopoly

In the long-run, the firm optimally adapts capacities. Throughout the analysis we assume that the fixed capacity costs are quadratic for both firms. In particular, we have that $\left[r_F K_F + 0.5\eta_F (K_F)^2\right]$ and $\left[r_I K_I + 0.5\eta_I (K_I)^2\right]$ represent the fixed costs of the flexible and intermittent firm, resp. This implies linear marginal capacity costs for both the flexible and intermittent technology. For reasons of transparency, we again consecutively focus on the behavior under monopoly and duopoly.

4.1. Capacity choices of a monopolist

First, consider the monopolist's capacity choices. The firm's long-run problem is

$$\begin{aligned} \max_{K_F, K_I} \; & P(q_F^M + K_I) * (q_F^M + K_I) - \mu C(q_F^M; K_F) - (1-\mu) C(q_F^M + K_I; K_F) \\ & - \left[r_F K_F + 0.5\eta_F (K_F)^2\right] - \left[r_I K_I + 0.5\eta_I (K_I)^2\right] \\ s.t. \quad & q_F^M + K_I \leq K_F \\ & K_F \geq 0; K_I \geq 0 \end{aligned}$$

where optimal short-run output depends on capacities, as determined in (7) above.

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 the first-order condition for the firm's output choice (3), the first-order conditions for optimal capacities can be written as

$$-\left[\mu\frac{\partial C(q_F^M;K_F)}{\partial K_F}+(1-\mu)\frac{\partial C(q_F^M+K_I;K_F)}{\partial K_F}\right]-r_F-\eta_F K_F=0$$
$$(P')(q_F^M+K_I)+P-(1-\mu)\frac{\partial C(q_F^M;K_F)}{\partial q_F^M}-r_I-\eta_I K_I=0. \tag{13}$$

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.

To get more insight, we return to the specifications used before, see (4) and (5). The two first-order conditions given in (13) can then be written as

$$\mu\delta q_F^M+(1-\mu)\delta(q_F^M+K_I)-r_F-\eta_F K_F=0 \tag{14}$$

$$a-2b(q_F^M+K_I)-(1-\mu)(c-\delta q_F^M)-r_F-\eta_F K_F=0. \tag{15}$$

They can be rearranged so that

$$K_F^M=\frac{\delta(a-c)-2\delta b\mu K_I^M-2br_F}{2b\eta_F-\delta^2} \tag{16}$$

$$K_I^M=\frac{\mu c-r_I-\mu\delta K_F^M}{\eta_I}. \tag{17}$$

Note that second-order conditions require

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

In Appendix 1 we solve (16)-(17) for the two optimal capacities as functions of the parameters only. The analytic solutions are fairly complex; however, we show that they immediately imply

$$\frac{\partial K_F^M}{\partial r_F} < 0; \quad \frac{\partial K_F^M}{\partial r_I} > 0; \quad \frac{\partial K_I^M}{\partial r_I} < 0; \quad \frac{\partial K_I^M}{\partial r_F} > 0. \tag{18}$$

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 $q_F^M + K_I \le K_F$ is binding at the optimum. Using earlier results (see (8)), this happens when at the optimal capacity choice it holds that

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

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

After substitution of the constraint into the objective function and reconsidering the choice of optimal capacities, we then have the first-order conditions

$$K_F = \frac{a - c - \mu\delta K_I - r_F}{2(b+\delta) + \eta_F} \tag{19}$$

$$K_I = \frac{\mu c - r_I - \mu\delta K_F}{\eta_I}. \tag{20}$$

The solution reported in Appendix 1 shows that the effects of capacity costs on optimal capacities have the same signs as in (18) 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.

4.2. Capacity choice under duopoly

We now focus on the duopoly setting. At the capacity stage, the flexible firm

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

As will become obvious, the capacity constraint is crucial under duopoly. The set of first-order conditions is

$$\mu\left[\delta q_F^D\right]+(1-\mu)\left[\delta(q_F^D+K_I)\right]-r_F-\eta_F K_F+\lambda\le 0$$
$$\left\{\mu\left[\delta q_F^D\right]+(1-\mu)\left[\delta(q_F^D+K_I)\right]-r_F-\eta_F K_F+\lambda\right\}K_F=0$$
$$q_F^D+K_I-K_F\le 0$$
$$\left\{q_F^D+K_I-K_F\right\}\lambda=0.$$

Let us first assume an internal solution. The first-order condition for optimal capacity can then be written as

$$\delta q_F^D+\delta(1-\mu)K_I=r_F+\eta_F K_F.$$

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, by using the duopoly output q_F^D of the flexible producer as given in (10), yields the reaction function

$$K_F^D=\frac{\delta(a-c)-\delta b\mu K_I^D-(2b)r_F}{2b\eta_F-\delta^2}. \qquad (21)$$

The denominator is positive by the second-order condition, so that flexible capacity declines in both capacity cost parameters r_F,η_F. Of course, δ should be sufficiently positive so that $K_F^D>0.$ The reaction function is also downward sloping in intermittent capacity. The firm has enough capacity to cope with total demand, by assumption, and more intermittent capacity implies lower average production. Indeed, average production

$$\mu q_F^D+(1-\mu)(q_F^D+K_I^D)=\frac{a-c+\delta K_F^D-\mu b K_I^D}{2b}$$

is declining in intermittent capacity and the capacity factor μ of the intermittent firm.

Turning to the capacity problem of the intermittent firm, this can be formulated as

$$\max_{K_I}\ \mu\left[a-b\left(q_F^D+K_I\right)\right]K_I-r_I K_I-0.5\eta_I(K_I)^2.$$

Substituting the flexible output (10) we can write this objective function as

$$\max_{K_I} \mu\left[a-b\left(\frac{a-c-b(2-\mu)K_I+\delta K_F}{2b}+K_I\right)\right]K_I - r_I K_I - 0.5\eta_I (K_I)^2.$$

Solving the first-order condition leads to the reaction function

$$K_I^D = \frac{\mu(a+c)-\mu\delta K_F^D - 2r_I}{2(\mu^2 b+\eta_I)}. \tag{22}$$

The second-order condition is easily shown to be satisfied. Observe from (22) that more flexible capacity reduces intermittent optimal 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, wherefrom the intermittent producer strategically decreases its capacity K_I^D.

We can solve the reaction functions for the two optimal capacities, see Appendix 2. As before, the solutions are not very informative, except that they imply

$$\frac{\partial K_F^D}{\partial r_F} < 0; \quad \frac{\partial K_F^D}{\partial r_I} > 0; \quad \frac{\partial K_I^D}{\partial r_I} < 0; \quad \frac{\partial K_I^D}{\partial r_F} > 0. \tag{23}$$

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. The signs are as under monopoly, at least provided the optimum is internal.

Therefore, the more interesting case to consider under duopoly is the situation where the capacity restriction of the flexible producer is binding. 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 (22) given before. For the producer operating with the flexible technology, however, the requirement to satisfy demand — even if the intermittent competitor does not produce any output at the time of delivery (because of absence of wind or solar energy) — has severe implications. To see this, assume that the unconstrained problem yields a solution where $q_F^D + K_I^D > K_F^D$. Using (10), this boils down to

$$K_F^D < \frac{a-c+\mu b K_I^D}{2b-\delta}.$$

In that case, the flexible firm is required to offer capacity that satisfies $q_F + K_I = K_F$, or equivalently

$$K_F = \frac{a - c + \mu b K_I}{2b - \delta}. \tag{24}$$

The constraint is obviously increasing in intermittent capacity. Therefore, 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 (23) 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 (22) together with (24), we find the solution in the case of a binding capacity restriction on the flexible producer:

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

The capacity constraint implies that the capacity costs of the flexible firm, neither η_F nor r_F, play no role at all in the optimal capacities. The intuition is that 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 *reduces* flexible capacity. The reason is that when intermittent capacity becomes more expensive intermittent capacity declines; but this in turn makes the capacity constraint less stringent and allows the flexible firm to reduce its capacity. It knows that when there is no wind, less production will have to be delivered. In this sense, if the constraint binds, capacities of the two technologies are strategic complements.

The analysis under duopoly 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 (24). 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*.

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, under duopoly, more intermittent capacity imposes a costly constraint on the flexible producer by raising reserve requirements in case no intermittent generation is available. 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

$$\mu\left[\delta q_F^D\right]+(1-\mu)\left[\delta(q_F^D+K_I)\right]-r_F-\eta_F K_F+\lambda=0$$
$$q_F^D+K_I-K_F=0.$$

Substituting the firm's optimal output -- as given by expression (10) -- into these conditions and totally differentiating this two-equation system yields after straightforward calculations[15]

[15] 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. This was pointed out in Section 3.2.

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

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.

4.3. Capacity choices under monopoly and duopoly: implications

The problem of optimal capacity choices under different market structures has some simple but relevant implications. First, when a monopolist operates the two generation technologies, both capacities are considered as substitutes. This is 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 sufficiently low capacity costs of the intermittent technology, the intermittent firm installs such a high level of intermittent capacity, and at some point the flexible producer will hit the capacity constraint. This forces the flexible firm to install more capacity in response to to the high level of installed intermittent capacity. Due to the requirement – if intermittent generations conditions are unfavorable – of having to cover the 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. In this case, the availability of more intermittent capacity imposes a negative externality on the flexible producer, forcing him to increase capacity.

Second, the direct comparison between equilibrium capacities under monopoly and duopoly (as reported in Appendices 1 and 2), does not yield unambiguous results. Depending on parameter values each market structure may yield the largest total capacity. Two clear insights can be derived, however. One is that, by comparing the internal solutions (16) and (21) we find that, conditional on a given intermittent capacity, a monopolist will offer less flexible capacity than under duopoly. This seems intuitive as monopoly results in higher prices and less total demand than duopoly. The other insight refers to the effect of increasing marginal capacity costs. Comparing the expressions reported in Appendices 1 and 2 we easily show that higher marginal capacity costs have larger implications under monopoly than under duopolistic competition.

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

Proposition 2. 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 become strategic complements.**
b. **If it is optimal for the flexible producer to install sufficient capacity so that the constraint is not binding, intermittent and flexible capacities are strategic substitutes.**
c. **The shadow price of the constraint on reserve capacity is increasing in intermittent capacity.**

5. Policy implications

The finding that the capacity restrictions makes intermittent and flexible capacities strategic complements has obvious policy implications. First, it means that subsidizing intermittent capacity (reducing the firm's capacity cost) may be desirable as long as intermittent production is quite limited. With a strong and growing intermittent production sector, subsidies may have perverse effects, however. They raise the chances that flexible producers will have to increase capacity to meet all demand under unfavorable intermittent generation conditions. More intermittent capacity, then, implies additional dispatchable capacity investment, imposings a negative externality on flexible producers.

Second, subsidies to flexible capacity have 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.

The focus of this paper has been on the strategic choice of capacity with dispatchable and intermittent generation. Our simplifying assumption that the flexible producer must sell at the market-clearing price when intermittent generation conditions are unfavorable could be adjusted. In practice, dispatchable firms offer power in the reserve market at higher prices to producers that fail to deliver their announced quantities in the day-ahead market. In addition, price volatility has significantly increased in wholesale markets where intermittent capacity has entered. In Bouckaert and De Borger (2013), the intermittent firm creates demand uncertainty, since it needs power when its generation conditions are unfavorable. We show that when the flexible firm announces a quantity and price for each state of nature, the intermittent firm still exerts a negative externality on its capacity choice.

6. 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 under monopoly

We start from (16)-(17), reproduced here for convenience

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

$$K_I = \frac{\mu c - r_I - \mu\delta K_F}{\eta_I}.$$

Rearranging and solving these two equations by Cramer's rule, we find that

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

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

This immediately establishes the results

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

These results are as expected.

If the capacity constraint is binding, we had the conditions

$$K_F = \frac{a - c - \mu\delta K_I - r_F}{2(b+\delta) + \eta_F} \text{ and } K_I = \frac{\mu c - r_I - \mu\delta K_F}{\eta_I}.$$

The solutions are now

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

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

Appendix 2: capacity choices under duopoly

We solve (21)-(22) by Cramer's rule. We find:

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

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

Capacity cost effects are as expected since

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

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

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

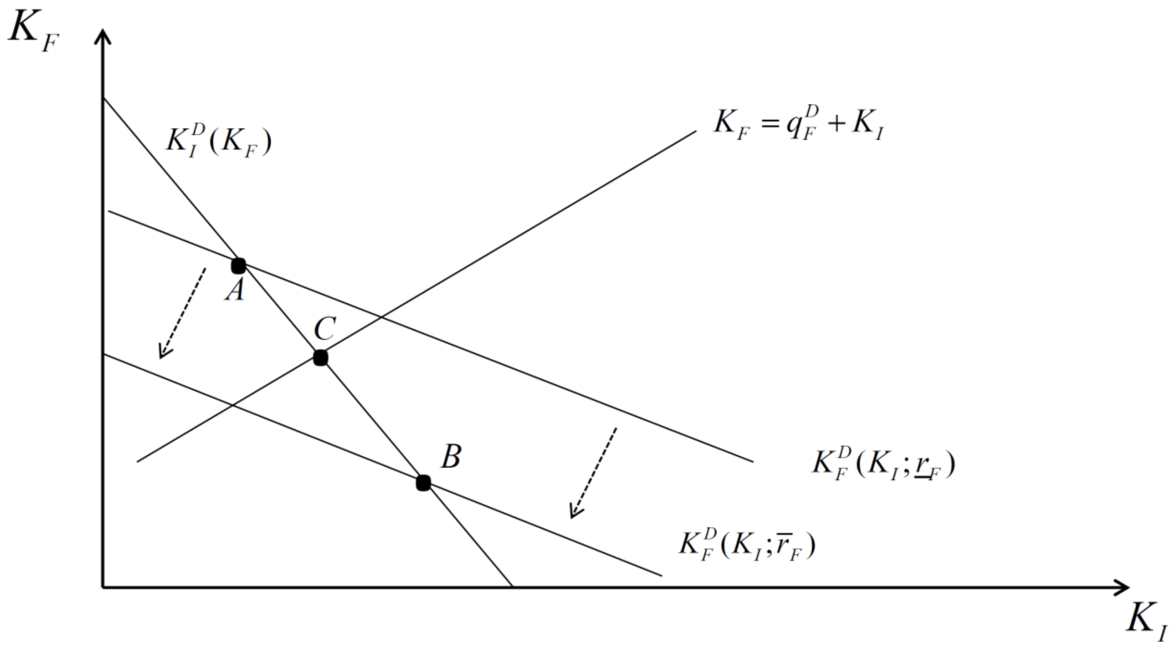
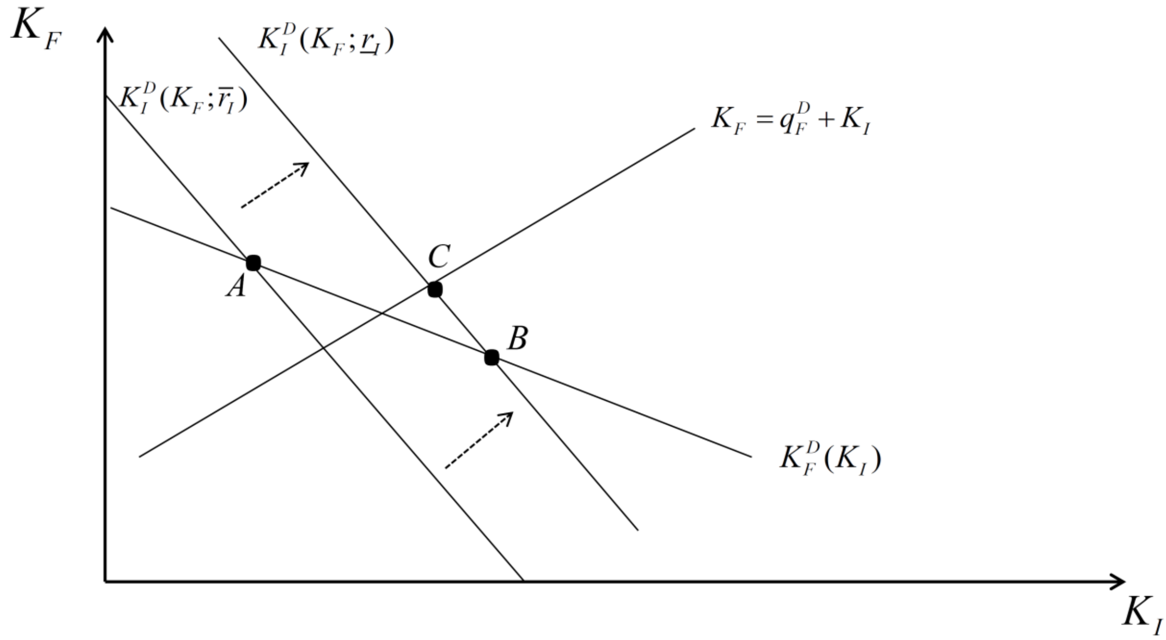


Figure 2: a decrease in the investment cost of intermittent capacity.



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