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Systèmes
Energétiques

Working Paper n°18

December 2008

Capacity choice, Technology mix and market power

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December 2, 2008

Abstract

This paper investigates strategic capacity choices in an electricity markets with heterogenous firms. With a competitive wholesale market, the paper focusses on long term strategic investment. Two technologies are available to produce electricity, both are efficient and used at a first best optimum. When all firms cannot invest in both technologies there can be over investment in one of these. Furthermore, even a firm that can invest in both may be deter from investing in one of them and specialized. If the number of firms that can invest in a particular technology is limited, the development of competition only through the other technology can decrease welfare.

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Résumé

Cet article étudie le choix stratégique de capacité de production dans un système électrique avec une demande variable (représentée par une courbe de charge) et deux technologies disponibles (base et pointe). Les deux technologies se distinguent par leurs structures de couts (ratio cout de capacité/cout variable) et sont efficaces en ce sens qu'elles sont toutes deux utilisées à l'optimum.

L'analyze s'interresse non seulement à la capacité totale mais aussi au mix technologique: la répartition de cette capacité totale entre les deux technologies. Le marché de court terme est supposé compétitif, ou parfaitement régulé, et l'analyse se focalise sur les décisions de long terme des firmes. Il est supposé que les firmes productrices ne peuvent pas toutes investir dans les deux technologies. Certaines sont spécialisées alors que d'autres sont généralistes. Cela permet de représenter le fait que certaines technologies nécessitent un savoir-faire particulier que seules certaines firmes possèdent alors que d'autres technologies sont plus standardisées. Cette hétérogénéité des firmes a des implications sur les choix d'investissement et le nombre de firmes de chaque type affecte le bien-être de façon non monotone.

Il est tout d'abord établi qu'une firme généraliste peut être incitée à se spécialiser à l'équilibre dans l'une des technologies: elle n'aura pas d'incitation à investir dans l'autre pour éviter de trop baisser le revenu obtenu des capacités de son choix de technologie. De plus on s'interresse aux effets d'un changement du nombre de firms spécialisée dans l'une des technologies. Il est montré, qu'une augmentation du nombre de firmes spécialisées augmente la capacité totale investie mais diminue la capacité de l'autre. La perte liée à la distorsion du mix technologique peut être supérieure au gain lié à l'augmentation de la capacité totale. Ainsi, bien que les deux technologies soient efficaces, une augmentation du nombre de firmes ayant accès à l'une de ces technologies peut diminuer le surplus collectif.

1 Introduction

One motivation behind the market reforms in electricity industries is to encourage efficient investment in the optimal mix of technologies in a timely way and to avoid situations of overcapacity observed in the former regime of regulated monopoly. But there are growing concerns about the ability of the new liberalized market regime to induce sufficient investment in building capacity, in the optimal technology mix without penalizing efficient but capital intensive technologies. Ensuring enough generation capacity to meet future electricity demand by the optimal technology mix progressively became a contentious issue in the design of the reforms, particularly since some recent crisis.

Three main reasons are highlighted in the literature to explain the sub-optimality of investment in generation mix: ”missing money”, risk management, and market power. The present chapter focuses on the third reason: the strategic choice of generating capacity. I do not consider the interrelation of long term investment choice with short term market power. It is assumed that the short term is perfectly regulated: the wholesale price is set at the marginal cost of the marginal technology or at the value of the capacity constraint when it is binding. The aim is to analyze the long term incentive for generators to underinvest in aggregate capacity and to distort the generation mix. Particularly, the influence of the number of firms that have access to various technologies is emphasized.

The current situation of electricity markets and the three explanations of underinvestment are reviewed before the theoretical literature on capacity choice in electricity markets and the contributions of the present paper.

Sub-optimality of generation investment in electricity markets

The electricity industry has the particular feature that many technologies are used to produce the same good, there is not a benchmark technology but a set of technologies. For any particular load duration curve, an optimal technology mix minimizes the cost to produce this load. A technology can be described by its ratio of variable and capacity cost[1]. A baseload technology is characterized by a high capacity cost and a low variable one, it is used to produce during a long fraction of time, whereas peaking units are characterized by a low capacity cost and high operating one and are efficient to produce during few hours per

[1] It is a first approximation because others characteristics play important rules such as the ramping rate.

years.

A perfectly competitive wholesale electricity markets should theoretically induce efficient investment: an optimal aggregate capacity and an optimal technology mix. Scarcity rents during the peak periods are needed to ensure the profitability not only of peaking units but also of all other technologies. Moreover the short term system security of the system is a public good supplied by the system operator with operating reserves(Joskow and Tirole; 2007). It implies that additive revenues are needed for the contribution of capacities to this public good.

Concerns on investment that initially focuses on peaking units are now extended to all technologies. Particularly, the ability of wholesale electricity markets to promote sufficient investment in capital intensive technologies, such as nuclear which is a typical baseload technology, is currently a debated issue. Three main arguments are found in the literature to explain the potential lack of investment in electricity markets.

The first explanation for underinvestment: the ”missing money” refers to the deficit of revenue during peak hours. This deficit is attributed to price cap (Cramton and Stoft; 2006) and to ill designed regulatory procedures related to the public good attributes of operating reserves. Despite price caps that are considered too low, the technical rules used by system operators to guarantee system reliability by calling operating reserves tend to erase revenues from the energy and reserves markets as explained by Joskow (2006). Even if the price cap can be suppressed, it remains a deficit of revenues.

The second reason is the exceptional volatility of electricity prices and markets incompleteness. The volatility of electricity prices (with a magnitude from 20€to 5-10 000€/MW/h) is explained by the short-run inelasticity of demand and supply, given the non price transmission and the non-storable nature of electricity. In principle volatility does not deter to invest in due time and in appropriate technologies, provided that future and forward markets exist to allow investors to manage their market risks. But in electricity markets these markets are little developed, this incompleteness creates difficulty for hedging investment in generation. Risk and market incompleteness are often cited as explanations of the vertical integration observed in electricity markets (Finon; 2008; Joskow; 2006). Furthermore, Roques et al. (2006) argue that risk aversion can favor investment in combined cycle gas turbine (CCGT) compared to nuclear plant because of the correlation between electricity prices and gas price. By decreasing the variance of the revenue from a CCGT, this correlation favors gas plant. So risk aversion can explain a perceived lack of investment in nuclear plant.

The third reason refers to market power and is the subject of the present paper. Every generator can potentially benefit from a sub-optimal investment in generation capacity in the system, which will provoke profitable periods of price spikes. Indeed, because of the inelastic nature of demand and supply, even a slight shortfall of available capacity or unexpected high loads can provoke a dramatic increase in price in period of tight supply. Hence generators are incited to under-invest. European Commission suspects that the electricity companies delay investment in baseload and midload generation, beyond the remaining regulatory uncertainty, because in any case they would be the winners of any situation of tight supplies (D.G.COMP; 2007).

Moreover, beside the incentive to underinvest in aggregate capacity firms may have also an incentive to profitably distort the technological mix. This distorsion may be amplified by the heterogeneity of firms relative to the access to technologies. Because some technologies necessitate a specific knowledge, that could have been acquired historically, all firms do not master all technologies and some are specialized whether others are "generalist". The present paper deals with this issue by analyzing the deficit of investment in several technologies related to strategic choice of capacity, and its relation with the number of firms that have access to each technology. I have in mind the current situation of nuclear technology and CCGTs, the later being a standardized technology that is perceived as the main vehicle of competition (Newbery; 1998). The theoretical literature related to market power and capacity choice is reviewed next.

Capacity choice

The development of wholesale electricity markets created a renewed interest in the literature on capacity choice with demand fluctuation or uncertainty. Gabszewicz and Poddar (1997) analyze the choice of capacity by two competing producers in a linear model. They establish that firms invest more with uncertainty than without. In their model, one technology is available and short term competition is a quantity game *à la* Cournot with capacity constraints. Their results are generalized by Zoetl (2008, chap1) who also considers the alternative assumption of a regulated, or perfectly competitive, spot market.

The issue of the technology mix has been addressed by several authors and in most papers all firms have access to all technologies. In a major contribution, von der Fehr and Harbord (1997) analyse investment by symmetric producers for different price mechanisms or regulatory regimes: they consider an efficient spot market and a non discriminatory auctions. In the later case, they state that there is no symmetric equilibrium[2] but only consider the duopoly case. With an efficient spot market, which is the case considered here, they establish that firms underinvest in aggregate capacity and profitably distort the technology mix toward peak units. A firm has an incentive to limit baseload investment in order to limit the period of marginality of this technology. An increase of the number of firms both increases the aggregate quantity of capacity and improves the technology mix. In a more recent paper Arellano and Serra (2007) establish a similar result, they consider the incentive for firms to distort the technology mix when the aggregate quantity of capacity is fixed and extend the analysis to free entry equilibrium.

Those results contrast with those obtained with short term Cournot competition. Because of the strategic effect on the short term of lower variable cost[3], there is a strategic incentive to invest in baseload capacities.Murphy and Smeers (2005) consider heterogeneous firms: a baseload and a peak producer. They emphasize the strategic effect of investment in a closed-loop equilibrium. Because of this strategic effect the baseload firm invest more in a closed loop equilibrium than in an open loop one[4]. Zoetl (2008, chap3) considers symmetric firms that have access to a continuous technology set. The continuity property of the technology set allows tractability of the model and explain the symmetry of firms at equilibrium. He establishes that because of a strategic incentive firms might overinvest in baseload units.

To my knowledge, only Murphy and Smeers (2005) consider asymmetric firms, and no previous analysis perform comparative statics on the number of investing firms. It might be related to the analytical difficulties of dynamic

[2]This is similar to the result of Reynolds and Wilson (2000) on capacity choice under demand uncertainty and price competition. It is further analyzed by Fabra et al. (2008) who compare different auctions mechanisms.

[3]The strategic effect refers to the decrease of others' productions subsequent to a decrease of one's marginal cost.

[4]In the open loop equilibrium strategic effects are ignored, capacities and (conditional) production quantities are simultaneously fixed.

games with discrete technology sets and strategic interactions at each stages. To provide such an analysis, short term market power is ignored here and so is the strategic effect mentioned above. It is assumed that the price is set at the variable cost of the marginal technology when demand is not rationed and at the value of lost load (VoLL) when rationing occurs. Empirically, observed prices are not as high as predicted by theoretical models of imperfect competition (supply function, discrete auctions, Cournot) and more close to marginal cost than to "Cournot" prices(Wolfram; 1999). It can be justified by the fact that wholesale electricity markets are highly scrutinized by regulatory authorities, or auctions are "short term" efficient[5].

I consider here heterogeneous firms: all of them have not access to all technologies, some are specialized and some are generalist. It is first shown that even if both technologies are efficient, generalist firms do not necessarily invest in both. If the number of specialized firms in a particular technology is high compared to the rest of the industry, they overinvest in this technology and it deter generalist firms from investing in this technology. In such case each generalist firm behaves as a specialist one in the other technology.

Both the aggregate quantity of capacity and the technology mix are shown to be distorted in a variety of direction that is related to the number of firms that can invest in each technology. The welfare consequences of a change in the number of firms that have access to a technology are investigated. The respective numbers of baseload and peak firms influence both aggregate capacity and the technology mix. It is established that even if both technologies are efficient an increase of the number of one kind of specialized firms can decrease welfare. If an additional firms is active despite increasing capacity it can further distort the technology mix and the cost of this distortion can offset the welfare gain from the increase in capacity. Hence, if the number of firms that have access to a particular technology is fixed, the number of firms that have access to the other technology should be limited.

For instance, the deficit of investment in nuclear can be related to the number of firms that are effectively able to invest in nuclear plants, this deficit can also explain an overinvestment in other technologies such as CCGTs.

The rest of the chapter is organized as follow, I first introduce the model and

[5] Another explanation is the vertical relations between electricity producers and retailers that are not considered here.

consider the first best optimum in the next section. Then the investment game is solved in the general case(section 3) before analyzing the influence of the number of firms of each type (section).

2 The model

2.1 Framework

I consider a simple electricity system without network constraints. Consumers are assumed to be insensitive to price, the demand of electricity x is uniformly distributed on the set $[0, X]$ with the density $1/X$. It is a rough representation of a load duration curve with a year duration normalized at 1. In section I discuss how a more realistic load duration curve would influence results. The surplus from each unit of electricity consumed is assumed constant and denoted v.

There are two technologies that can be used to produce electricity labeled $t = \alpha, \beta$. Each technology t is characterized by a variable cost c_t (per kwh) and a capacity cost I_t (per kW per year). Technology α is less costly to produce a unit of electricity all over the year than technology β, but it is more costly for production over short period of time:

$$\begin{aligned} c_\alpha + I_\alpha &< c_\beta + I_\beta \\ I_\beta &< I_\alpha \end{aligned}$$

Even if the sum of variable and capacity cost of technology β are higher than those of technology α, it is efficient for production during a short fraction of the year. The difference of capacity costs is denoted $\Delta = I_\alpha - I_\beta$ and the difference of variable costs $\delta = c_\beta - c_\alpha$. Both are positive and $\Delta < \delta$. The ratio $r = \Delta/\delta$ is the duration such that technology α (resp. β) is more efficient for production over period more (resp. less) than r. These features are illustrated on figure 1.

Technologies α and β are respectively called baseload and peak through the paper, but the framework can be used to consider baseload and midload technologies such as nuclear and CCGT.

For $t = \alpha, \beta$, the ratio $r_t = I_t/(v - c_t)$ is the minimal duration of production with technology t such that the aggregate cost is less than the consumer surplus. Both are assumed less than one i.e. $v > c_\beta + I_\beta$ and it is assumed that:

$$r_\beta < r$$

This assumption ensures that technology β is used at equilibrium. The left hand side is the minimal duration of production with technology β such that cost are below consumer surplus. To produce during a smaller period of time with this technology a unit of electricity consumed would imply a welfare loss. The right hand side is the maximal duration of production for which technology β is more efficient than technology α. So the former is smaller than the latter and it is optimal to use both technologies to produce electricity. It should be noticed that this assumption is equivalent to $r_\alpha < r$ and to $r_\beta < r_\alpha$, these two inequalities can be interpreted similarly.

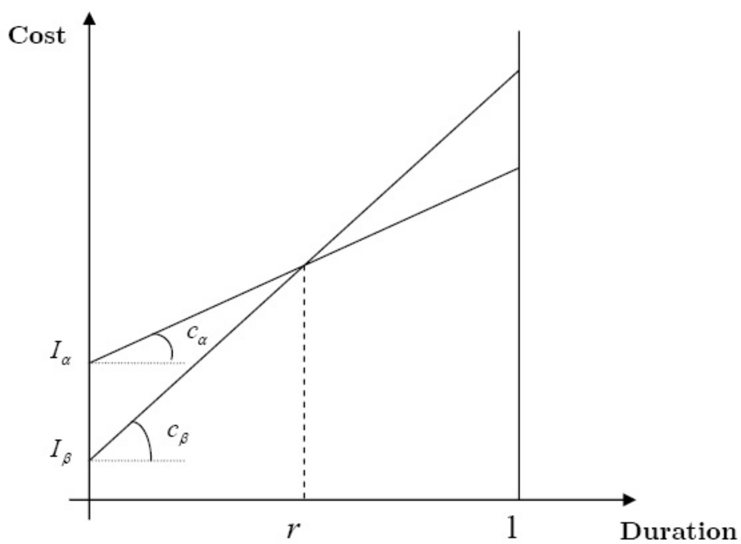

Figure 1: Cost and production duration

There are n firms that produce electricity indexed $i = 1..n$. Individual quantities of capacity of firm i of each technology are denoted k^i_α and k^i_β, and its aggregate quantity of capacity is denoted $k^i = k^i_\alpha + k^i_\beta$. So aggregate quantities over all firms of capacities of each technology are $k_t = \sum_i k^i_t$ for $t = \alpha, \beta$ and $k = k_\alpha + k_\beta$.

All firms have not access to both technologies, so the set of firms is divided into three subsets. There are g 'generalist' firms that have access to both technologies and $n-g$ specialized firms: s_α baseload firms have only access to technology α and s_β peak firms that have only access to technology β. So the number of firms is $n = g + s_\alpha + s_\beta$. Firms are ordered as follows: firm $i = 1, .., s_\alpha$ are baseload firms, firms $i = s_\alpha + 1, .., s_\alpha + s_\beta$ are peak firms and finally firms $i = n - g, .., n$ are generalist firms.

Each generalist firm chooses quantities of capacity of each technology, whereas a peak (resp. baseload) firms only chooses a quantity of technology β (resp. α).

Once capacities are fixed, short term is assumed 'perfectly' regulated: there is no modeling of short term market power. The price is set at the marginal cost of the last unit called when all demand is satisfied and at v in case of rationing. Firms produce with a technology when the price is above its operating cost. Rationing occurs when the demand of electricity is higher than the aggregate capacity available. So, when demand is less than k_α the wholesale price is c_α, and the production of x is done by firms that have baseload capacities. When demand is greater than k_α and smaller than k the price is c_β, baseload capacities are fully used and the $x - k_\alpha$ remaining quantity is produced by firms with peak capacities. For higher demand the price is v and there are only k units of electricity consumed, a part $x - k$ of the demand is not satisfied[6]. Price and quantities are represented on figure 2.

[6] I do not consider the cost of inefficient rationing. With a linear loss of $\gamma(x-k)$ in case of rationing the price would be $v + \gamma$ when $x > k$.

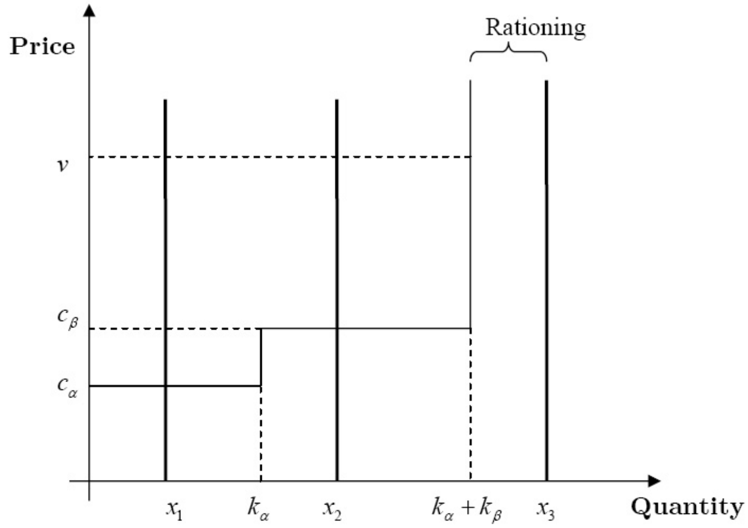

Figure 2: Supply curve and spot prices

Firms earn short term positive revenue from capacities of a technology type only when the aggregate quantity of capacity of this type is fully used. The profit of a firm $i = 1, .., n$ is:

$$\begin{aligned} \pi^i &= \frac{1}{X}\int_{k_\alpha}^{k_\alpha+k_\beta} \delta k_\alpha^i \, dx \\ &+\frac{1}{X}\int_{k}^{X} \left[(v-c_\beta)k_\beta^i + (v-c_\alpha)k_\alpha^i\right] dx \\ &-I_\alpha k_\alpha^i - I_\beta k_\beta^i \end{aligned} \tag{1}$$

The net revenue of a firm has two terms: the first one is the net revenue from baseload capacity when the price is set the variable cost of the peak technology and the second one is the profit obtained from both technologies when rationing occurs. Alternatively one can write the profit of a firm as a function of aggregate capacity and baseload capacity:

$$\begin{aligned} \pi^i &= \frac{1}{X}\int_{k_\alpha}^{X} \delta k_\alpha^i \, dx \\ &+\frac{1}{X}\int_{k}^{X} (v-c_\beta)k^i \, dx \\ &-\Delta k_\alpha^i - I_\beta k^i \end{aligned} \tag{2}$$

This writing emphasizes the relation between the technology mix and the aggregate quantity of capacity of a generalist firm. In that case, the cost of a unit of capacity of technology α is net of the cost of the unit of capacity β it replaces and similarly its short term revenue is the variable cost difference in all states where baseload capacity are fully used.

2.2 Welfare optimum

Welfare is the sum of gross consumer surplus and aggregate production cost. Gross consumer surplus is only related to the aggregate quantity of capacity, it is denoted $S(k)$; the aggregate cost of production is related to the technology mix and can be written as a function of aggregate capacity and the quantity of capacity of technology α: $C(k, k_\alpha)$. These two functions are:

$$S(k) = \frac{v}{X}\left[\int_0^k x\,dx + \int_k^X k\,dx\right] = \frac{v}{X}\left(X - \frac{k}{2}\right)k \tag{3}$$

$$\begin{aligned} C(k, k_\alpha) &= \frac{1}{X}\left[\int_0^k c_\beta x\,dx + \int_k^X c_\beta k\,dx\right] \\ &\quad -\frac{1}{X}\left[\int_0^{k_\alpha} \delta x\,dx + \int_{k_\alpha}^X \delta k_\alpha\,dx\right] + \Delta k_\alpha + I_\beta k \end{aligned} \tag{4}$$

And welfare is:

$$W(k_\alpha, k) = S(k) - C(k, k_\alpha) \tag{5}$$

The problem can alternatively be solved with respect to couple of quantities (k_α, k_β) or (k_α, k). I proceed with the second method. Welfare (5) is concave and first best quantities k^* and k_α^* solve following first order conditions :

$$(v - c_\beta)\frac{X - k}{X} = I_\beta$$

$$\delta\frac{X - k_\alpha}{X} = \Delta$$

The first relation can be rephrased with the jargon of electricity systems. It is the relation between the value of lost load v and the loss of load probability $(X - k)/X$ and the operating and capacity costs of the peak technology. The second equation is related to the optimal technology mix that minimizes the cost of production. This technology mix is such that the time of use of each unit of capacity of technology β is less than r. From these equations it is straightforward to obtain the expression of the optimal technology mix:

$$k^* = X(1 - r_\beta) \text{ and } k_\alpha^* = X(1 - r), \; k_\beta^* = X(r - r_\beta) \tag{6}$$

And the assumption $r > r_\beta$ ensures that both technologies are used at the optimum. Furthermore, it is optimal to ration consumers during a fraction r_β of the year. This fraction is solely determined by the cost of the marginal technology and the value of lost load. The choice of first best quantities of capacities is represented on figure (3).

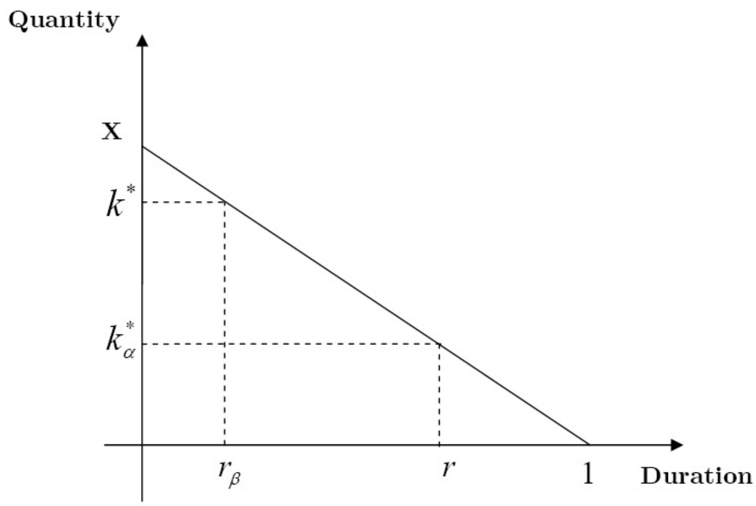

Figure 3: Load curve and optimal investment

I consider several industry configurations whether firms have access to both or only one technology. In the electricity industry some technologies are "standardized" and available to all firms whereas some others are not. There is an important concern on the ability of electricity markets to promote investment in peaking units, technology β in the framework. Beside the public good characteristics of operating reserves[7], few firms invest in peak capacities so they might limit their investment in order to increase the duration of periods of high prices.

[7] This public good aspect is not represented here because there is no risk of network collapse. The system operator is able to ration consumers before such event happens.

Nevertheless, concern about underinvestment can be extended to all type of technologies and particularly to baseload ones. Nuclear technology is a typical baseload technology characterized and few firms are able to master this technology, the situation described above is reversed: there is a potential lack of investment in baseload technology. So, both situations are analyzed below.

First, in the next section, the general case is described, the major issue being whether generalist firms specialize. Second, in the last section welfare consequences of an increase of the number of specialized firms of one type are described.

3 Oligopolistic equilibrium

Firms simultaneously choose their quantities of capacity in order to maximize their profit. Whereas specialized firms only invest in one type of capacity, generalist ones invest in both. From the expression (1), first order conditions of both types of specialized firms are:

$$\begin{aligned}\text{for } i &= 1,..,s_\alpha : \frac{\delta}{X}k_\beta + \frac{v-c_\alpha}{X}\left(X-k-k_\alpha^i\right) - I_\alpha = 0 \\ \text{for } i &= s_\alpha+1,..,s_\alpha+s_\beta : \frac{v-c_\beta}{X}\left(X-k-k_\beta^i\right) - I_\beta = 0\end{aligned}$$

As in an usual quantity game, firms have an incentive to limit their investment. Here, a lower aggregate capacity increases the length of time with price at v. Baseload firms have an additive revenue when price is fixed at c_β, this revenue is proportional to the quantity of peak capacity installed.

Concerning generalist firms, each of them chooses both quantities of capacity, as they might not invest in one type of capacity positivity constraints are introduced. So the objective of a generalist firm is:

$$\max_{k_\alpha^i,k_\beta^i}\{\pi^i(k_\alpha^i,k_\beta^i,k_\alpha,k_\beta)\}$$
$$\text{subject to } 0 \leq k_\alpha^i \text{ , } 0 \leq k_\beta^i$$

The Lagrange multiplier of the positivity constraint of baseload (resp. peak) capacity is ν_i (resp. μ_i). First order conditions of a generalist firm are for

$i = n - g + 1, .., n$:

$$\frac{\delta}{X}k_\beta + \frac{v - c_\alpha}{X}\left(X - k - k_\alpha^i\right) - \frac{v - c_\beta}{X}k_\beta^i - I_\alpha + \nu^i \ = \ 0$$
$$\frac{v - c_\beta}{X}\left(X - k - \left(k_\alpha^i + k_\beta^i\right)\right) - I_\beta + \mu^i \ = \ 0$$

Several relations between quantities chosen by generalist and specialized firms can be deduced from these first order conditions. If a generalist firm invests in both types of technology it chooses an aggregate quantity of capacity similar to a peak firm. The marginal capacity of a generalist firm being a peak unit its marginal revenue is similar to that of a peak firm. But part of a generalist firm's capacity is baseload.

Compared to baseload firms, generalist firms have a different incentive to invest in baseload capacity because they use baseload capacity to favorably distort the technology mix and not to set the aggregate capacity. The marginal baseload capacity of a generalist firm has the additional negative effect of decreasing its revenue from peak capacity, so generalist firms invest less in baseload capacity than baseload firms. The incentive to distort the technology mix might be best seen with the alternative writing of the first order condition :

$$\frac{\delta}{X}\left(X - k_\alpha - k_\alpha^i\right) - \Delta + \nu^i - \mu^i = 0 \tag{7}$$

This emphasizes that the choice of a baseload capacity is made by comparison with a peak unit, so opportunity marginal revenue and cost are δ and Δ. Equation (7) said that a generalist firm limits the share of baseload technology in order to increase the time of marginality of peak units.

However, whether generalist firms invest in both type of capacities depends upon industry configuration. Rewriting first order conditions of a generalist firm:

$$\begin{aligned} k_\alpha^i &= k_\alpha^* - k_\alpha + \left(\nu^i - \mu^i\right)/\delta \\ k_\beta^i &= k_\beta^* - k_\beta + \left[\frac{v - c_\alpha}{v - c_\beta}\mu^i - \nu^i\right]/\delta \end{aligned} \tag{8}$$

If one group of specialized firms "overinvests", i.e. invests more than the corresponding first best quantity, generalist firms do not invest in their technology. As specialized firms have only access to one technology they have higher investment incentives than generalist firms, so such situations can occur at equilibrium. If there are too many specialized firms of one kind, these firms may over invest and deter generalist firms from investing in their technology. In such cases, the situation is similar to an entirely specialized industry.

In proposition (1) expressions of equilibrium quantities when generalist firms invest in both types of technology are established. Situations where generalist firms do not invest in one technology are precisely stated in proposition (2). Individual equilibrium quantity of capacity of a baseload (resp. peak) firm is k_α^S (resp. k_β^S), and equilibrium quantities of baseload and peak capacities of a generalist firm are k_α^G and k_β^G.

Proposition 1 *There is a unique Nash equilibrium of the capacity game. If at this equilibrium generalist firms invest in both types of capacity. Equilibrium quantities are:*

$$\begin{aligned}
k_\alpha^S\left(s_\alpha, s_\beta, g\right) &= \frac{X}{A}\left[\left(g+1\right)\left(1-r_\alpha\right)+s_\beta\frac{\delta-\Delta}{v-c_\alpha}\right] \\
k_\beta^S\left(s_\alpha, s_\beta, g\right) &= \frac{X}{A}\left[\left(g+1\right)\left(1-r_\beta\right)+s_\alpha\left(r_\alpha-r_\beta\right)\right] \\
k_\alpha^G\left(s_\alpha, s_\beta, g\right) &= \frac{X}{A}\left[\left(g+s_\beta+1\right)\left(1-r\right)-s_\alpha\left(r-r_\alpha\right)\right] \\
k_\beta^G\left(s_\alpha, s_\beta, g\right) &= \frac{X}{A}\left[\left(g+s_\alpha+1\right)\left(r-r_\beta\right)-s_\beta\left(1-r\right)\right]
\end{aligned}$$

Where $A\left(s_\alpha, s_\beta, g\right)=\left(g+s_\alpha+1\right)\left(g+s_\beta+1\right)-s_\alpha s_\beta\left(v-c_\beta\right)/\left(v-c_\alpha\right)$

From expressions of the proposition 1 threshold numbers of specialized firms that deter generalist firms from investing in one of both technologies can be determined. These numbers are such that one group of specialized firms invest more than the first best corresponding quantity.

Proposition 2 *Equilibrium quantities* k_t^S *and* k_t^G *for* $t=\alpha,\beta$ *are:*

- *If* $s_\alpha \geq \left(s_\beta+g+1\right)\left(1-r\right)\left(r-r_\alpha\right)^{-1}$ *baseload firms 'over invest' and generalist firms invest only in peak capacities and:*

$$\begin{aligned}
k_\alpha^S &= k_\alpha^S\left(s_\alpha, s_\beta+g, 0\right) \geq k_\alpha^*/s_\alpha \text{ and } k_\alpha^G = 0 \\
k_\beta^S &= k_\beta^G = k_\beta^S\left(s_\alpha, s_\beta+g, 0\right)
\end{aligned}$$

- *If $s_\beta \geq (s_\alpha + g + 1)(r - r_\beta)(1 - r)^{-1}$ peak firms 'over invest' and generalist firms only invest in baseload capacities and:*

$$\begin{aligned} k_\alpha^S &= k_\alpha^G = k_\alpha^S(s_\alpha + g, s_\beta, 0) \\ k_\beta^S &= k_\beta^S(s_\alpha + g, s_\beta, 0) \geq k_\beta^* / s_\beta \text{ and } k_\beta^G = 0 \end{aligned}$$

- *Else quantities are those expressed in proposition 1.*

Proofs of both propositions are in appendix A. The term 'overinvest' is employed in a particular sense here. In situations described, firms invest more than the first best quantity of a technology but less than a second best defined with a fixed quantity of the other technology. For instance, if the quantity of peak capacity is fixed at the equilibrium quantity, the quantity of baseload capacity that maximizes welfare is always higher than $s_\alpha k_\alpha^S$.

The 'overinvestment' result is due to the limited access to a technology. It occurs if there are too many specialized firms of one kind or too few generalist firms. If the number of generalist firms increases, occurrence of overinvestment and specialization of generalist firms are less likely. Both conditions cannot be satisfied simultaneously so generalist firms always invest at least in one technology.

Conditions of overinvestment and specialization can be rewritten with the share of specialized firms in the industry. Specialization of generalist firms to baseload or peak technology occurs if respectively:

$$\frac{s_\alpha}{n+1} \geq \frac{1-r}{1-r_\alpha} \text{ or } \frac{s_\beta}{n+1} \geq \frac{r-r_\beta}{1-r_\beta}$$

These inequalities allow to analyse the effect of r on specialization. Technology β can be viewed either as a midload or a peak technology, the former case correspond to high r whereas the later a r close to r_α. So, it appears from these equation that generalist firm are more likely to specialize to technology β if this technology is midload, i.e. r is small. And conversely, specialization to baseload technology is more likely when technology β is a peak technology.

Only generalist firms

In the particular case where there are only generalist firms, they invest in both type of technologies and equilibrium quantities are:

$$k_\alpha^G(0,0,n) = \frac{1}{n+1} k_\alpha^* \text{ and } k_\beta^G(0,0,n) = \frac{1}{n+1} k_\beta^*$$

These expressions are similar to those found by von der Fehr and Harbord (1997), the oligopoly quantities are qualitatively similar to those obtain in a linear Cournot model. The aggregate capacity chosen by firms is the optimal one by a factor of $n/(n+1)$, and moreover, the technology mix is also distorted in a similar proportion.

Interesting situations are those where some specialized firms are active. I briefly discuss the two cases where there are only one kind of specialized firm before devoting the last section to the case of a entirely specialized oligopoly and the welfare consequences of an increase of the number of specialized firms. This last part is actually general because even if there are generalist firms there might specialized.

Generalist and baseload firms

Originally there was a concern on a potential lack of investment in peaking units, this concern was related to the effect of aggregate capacity on the frequency of rationing network collapse. The lack of investment in peaking units can be related to market power and the limited number of firms that invest in peakers[8]. So one should consider that all firms can invest in baseload plants whereas only a subset can invest in peakers: $s_\alpha = 0$.

In that case, when generalist firms invest in both technologies expressions are relatively simple because generalist firms 'complete' the investment of baseload firms. From equations (8), the following relation is satisfied by equilibrium quantities:

$$\begin{aligned} k_\alpha^G &= \frac{1}{g+1}\left(k_\alpha^* - s_\alpha k_\alpha^S\right) \\ k_\beta^G &= \frac{1}{g+1}k_\beta^* \end{aligned}$$

Corollary 1 *If $s_\alpha (r - r_\alpha) \leq (g+1)(1-r)$ generalist firms invest in both types of capacity, and equilibrium quantities satisfy:*

$$\begin{aligned} s_\alpha k_\alpha^S + g k_\alpha^G &= \frac{g}{g+1}k_\alpha^* + \frac{s_\alpha}{g+1}\frac{1-r_\alpha}{n+1} \\ g k_\beta^G &= \frac{g}{g+1}k_\beta^* \end{aligned}$$

[8] It is the assumption made by Joskow and Tirole (2007) when they analyse underinvestment in peakers and two regulations: price caps and capacity paiement.

Generalist and peak firms

The situation might also be reversed if there are only few firms that can invest in baseload capacity. This situation can illustrate the case of nuclear investment. There are few firms that have access to this technology but much more that can invest in gas plant, the development of competition in the electricity industry was essentially awaited from investment in CCGTs.

If there are numerous firms that can invest in peak technology, generalist firms specialize. Otherwise, expressions of aggregate and baseload capacities are simple and comparable to standard linear Cournot quantities.

Corollary 2 *If $s_\beta (1-r) \leq (g+1)(r-r_\beta)$, aggregate equilibrium quantities are:*

$$gk_\alpha^G = \frac{g}{g+1}k_\alpha^* \text{ and } g\left(k_\alpha^G + k_\beta^G\right) + s_\beta k_\beta^S = \frac{n}{n+1}k^*$$

In that case the distortion of investment is simply related to respective numbers of firms. Because the incentive to invest in aggregate capacity of a generalist firm is similar to the incentive of a peak firm, expressions are more simpler than in the previous case.

4 Number of firms and welfare

I consider here a specialized industry: $g = 0$ and $n = s_\beta + s_\alpha$ and consider the consequence on welfare of an increase of the number of firms of one group the other being fixed.

When firms are specialized the number of firms that have access to a particular technology influences both aggregate quantity of capacity and the technology mix. These effects explain that the number of firms that can invest in either technology has not a monotonic effect on welfare.

Let consider first that the number of baseload firms, s_α, is fixed. An increase of the number of peak firms increases quantities of aggregate capacity and peak capacity but decreases quantity of baseload capacity. So even if the aggregate quantity of capacity tends toward the optimal one as s_β grows there is a loss due to the distortion of the technology mix. More precisely, welfare is quasi concave with respect to the number of peak firms. There is an optimal number of peak firms and any increase of s_β beyond this number decreases welfare.

Some calculations (cf appendix B) give the following derivative of aggregate quantities with respect to the number of firms:

$$\begin{aligned}\frac{\partial}{\partial s_\beta}\left(s_\alpha k_\alpha^S\right) &= -\frac{1}{A}s_\alpha\frac{v-c_\beta}{v-c_\alpha}k_\beta^S \\ \frac{\partial}{\partial s_\beta}\left(s_\beta k_\beta^S\right) &= \frac{1}{A}\left(s_\alpha+1\right)k_\beta^S\end{aligned}$$

Abstracting from integer constraint, one can consider the derivative of welfare with respect to s_β. Injecting first order conditions gives the following expression :

$$\frac{dW}{ds_\beta} = \left(v-c_\alpha\right)k_\alpha^S\frac{\partial}{\partial s_\beta}\left(s_\alpha k_\alpha^S\right) + \left(v-c_\beta\right)k_\beta^S\frac{\partial}{\partial s_\beta}\left(s_\beta k_\beta^S\right)$$

As an increase of the number of peak firms has opposite effects on quantities of baseload and peak capacities the gain from the increase of the peak capacity is compensated by the loss from the decrease of baseload one. Whether one effect dominates the other depends on the relative quantity of firms.

Proposition 3 *Welfare is quasi-concave with respect to s_β, It is increasing if an only if*

$$\left(s_\alpha+1\right)k_\beta^S(s_\alpha,s_\beta) \geq s_\alpha k_\alpha^S(s_\alpha,s_\beta)$$

Welfare is maximized at

$$s_\beta^*(s_\alpha) = \frac{v-c_\alpha}{s_\alpha\left(\delta-\Delta\right)}\left[1-r_\alpha+(s_\alpha+1)^2(r_\alpha-r_\beta)\right]$$

This proposition is demonstrated in appendix C. The welfare loss is related to the asymmetry of firms but one should notice that both technologies are efficient and used at the first best optimum. The loss is not related to an inefficiency of new firms but a disequilibrium between both types of firms.

Concerning consumer surplus, at first sight it is unclear whether net consumer surplus increases with an increase of peak firms. An increase of the number of firms increases the aggregate quantity of capacity so it increases gross consumer surplus but it also decreases the quantity of baseload capacity so the price of electricity increases for some level of demand and consumers loose on these states.

Net consumer surplus is:

$$CS(k_\alpha, k_\beta) = \frac{1}{X}\left[\int_0^{k_\alpha} (v - c_\alpha)\, x dx + \int_{k_\alpha}^{k_\alpha + k_\beta} (v - c_\beta)\, x dx\right]$$

And derivatives with respect to each technology capacity are:

$$\begin{aligned}
\frac{\partial CS}{\partial k_\alpha} &= \frac{1}{X}\left[\delta k_\alpha + (v - c_\beta)\,(k_\alpha + k_\beta)\right] \\
\frac{\partial CS}{\partial k_\beta} &= \frac{1}{X}(v - c_\beta)\,(k_\alpha + k_\beta)
\end{aligned}$$

So an increase of the number of peak firms modifies net consumers surplus of:

$$\begin{aligned}
\frac{dCS}{ds_\beta} &= (v - c_\beta)\,\frac{s_\alpha}{AX} k_\beta^S \left[\left(s_\alpha k_\alpha^S + s_\beta k_\beta^S\right)\left(\frac{s_\alpha + 1}{s_\alpha} - \frac{v - c_\beta}{v - c_\alpha}\right) - s_\alpha k_\alpha^S \frac{\delta}{v - c_\alpha}\right] \\
&= (v - c_\beta)\,\frac{s_\alpha}{AX} k_\beta^S \left[s_\beta k_\beta^S \left(\frac{s_\alpha + 1}{s_\alpha} - \frac{v - c_\beta}{v - c_\alpha}\right) + k_\alpha^S\right]
\end{aligned}$$

So consumers surplus is always increasing when an additive peak firm is active. The welfare loss is entirely supported by firms. However, consumers pay electricity at a higher price for some level of demand because of the decrease of baseload capacity but this loss is compensated by the overall increase of available capacity.

A similar analysis can be conducted on the number of baseload firms and similar results are obtained. If one more firm has access to baseload technology the quantity of baseload capacity increases whereas the quantity of peak capacity decreases. Even if the aggregate quantity of capacity increases welfare is not monotonic and there is an optimal number of firms that can invest in the baseload technology if the number of other firms is constant.

Proposition 4 *Welfare is quasi concave with respect to s_α , it is increasing if and only if*

$$(v - c_\alpha)\,\frac{s_\beta + 1}{s_\alpha} k_\alpha^S > (v - c_\beta)\, k_\beta^S$$

For any s_β there is an optimal number $s^*_\alpha(s_\beta)$ that writes

$$s^*_\alpha(s_\beta) = \frac{1}{s_\beta}\frac{1}{(r_\alpha - r_\beta)}\left[1 - r_\beta + (s_\beta+1)^2\frac{\delta-\Delta}{v-c_\beta}\right]$$

The proof is in appendix D. The effect on aggregate welfare of an increase of baseload or peak firms have similar qualitative properties on welfare. And consumers benefit from the entry of a baseload firm in all demand states because an increase of the number of baseload firms increases both the aggregate quantity of capacity and the quantity of baseload capacity so consumers gain in all demande states.

Those results can be compared to the analyses of a usual Cournot oligopoly with heterogeneous firms[9]. Within this standard framework an additive inefficient firm increases the aggregate production but decreases the production of efficient ones, the overall effect can be negative because of the reallocation of production from efficient to inefficient firms. Here, all firms are efficient, in the sense that both technologies are used at the first best optimum, nevertheless, an additive firm can decrease welfare by modifying the technology mix in the wrong direction.

5 Discussion

This section is devoted to the implication of a change of the load duration curve. The load duration curve used is a very rough simplification of a real one. It has been used to get explicit formula of quantities and further results. A more realistic representation that does not deeply modifies results is to consider that demand x is uniformly distributed on the set $[x^-, x^+]$ with $x^+ - x^- = X$. With this distribution of demand the first best optimum is depicted on figure (4). It can be seen that baseload capacity is translated of x^- whereas peak capacity is unchanged.

[9]In a recent paper Corchón (2008) provides a complete analysis of welfare loss with Cournot competition.

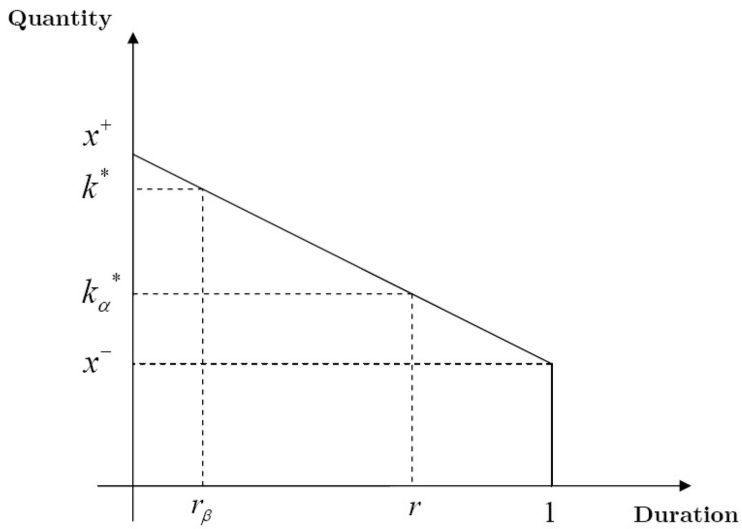

Figure 4: Load curve and optimal investment

Firms' choices are also modified, they all invest in greater quantities with this load duration curve. For instance, equilibrium individual capacity of a specialized baseload firm becomes:

$$k_\alpha^S = \frac{X}{A}\left[(g+1)\left(\frac{x^+}{X} - r_\alpha\right) + s_\beta \frac{\delta - \Delta}{v - c_\alpha}\right]$$

And other quantities change similarly. This change is not as benign as it might seem at first glance. The important consequence of this change is that the profit of baseload and generalist firms is not differentiable at $k_\alpha = x^-$ so they might invest in exactly the minimal quantity x^- of baseload technology and no more. In such case, on the short term, the baseload technology is never the marginal one and the price of electricity is never set at c_α.

Such situations arise if there are few baseload and generalist firms and $X = x^+ - x^-$ is sufficiently small, *i.e.* the load duration curve is sufficiently flat. Else, the analysis is not modified and results still hold.

6 Conclusion

In this chapter I analyzed investment by strategic firms in a simple electricity market perfectly regulated in the short term. This framework allowed to understand how firms have incentive both to decrease the aggregate quantity of capacity and distort the technology mix. The way the technological mix is distorted is related to the industry configuration. If one technology is not accessible to all firms there may be an overinvestment in the other technology.

Whereas both technologies are efficient, a firm that has access to both technologies does not invest in one of these technologies if there are too many specialized firms. If all firms are specialized an increase of a the number of firms of one type can decrease welfare. So, if the access to one technology is limited the number of firms active on the market via the other technology should be limited.

The development of competition via a unique technology whereas several are needed to ensure an optimal production of electricity is therefore questionable and can decrease welfare. Two major extensions are envisioned: the first would be to introduce an initial stage where firms can acquire either technologies by investing in a fixed cost, the second would be to analyse capacity markets and capacity payments that are implemented to correct investment incentives on electricity markets.

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Appendix

The following notation is introduced to facilitate exposition of calculations:

$$\gamma = \frac{v - c_\beta}{v - c_\alpha}$$

A Proof of propositions 1 and 2

Let assume that an equilibrium exists. It is clear from symmetry that all firms of a particular type invest in similar quantities at equilibrium. To establish existence and unicity of equilibrium I consider the three subcases whether generalist firms invest in both type of technologies or specialized in peak or baseload and show that these subcases cannot coexist.

Equilibrium quantities are: k_α^S, k_β^S and k_α^G, k_β^G which are respectively the individual capacity of baseload firms, the individual capacity of peak firms and the peak and baseload capacities of generalist firms.

1. Let assume that at equilibrium generalist firms invest in both technology types.

First I simplify the problem in order to get a simple linear system. As the individual aggregate quantity of a generalist firm is equal to the individual quantity of a peak firm: $k_\alpha^G + k_\beta^G = k_\beta^S$, the problem is already limited to three quantities: k_α^S, k_β^S and k_α^G.

The first order condition of peak firms writes:

$$s_\alpha k_\alpha^S + (s_\beta + g + 1)\, k_\beta^S = X(1 - r_\beta)$$

Furthermore, with the first order conditions of baseload firms and the one of baseload capacity of generalist firms it appears that $k_\alpha^S = k_\alpha^G + \gamma k_\beta^G$ so injecting the relation $k_\beta^G = k_\beta^S - k_\alpha^G$ the capacity of baseload firms is:

$$k_\alpha^S = (1 - \gamma)\, k_\alpha^G + \gamma k_\beta^S.$$

This relationship can be used to set a second relation between the capacity of a baseload firm and the one of a peak firm: $(s_\alpha + g + 1)k_\alpha^S + \gamma s_\beta k_\beta = X\,(1 - r_\beta)$. So the two quantities k_α^S, k_β^S satisfy the following system of equations:

$$\begin{bmatrix} s_\alpha + g + 1 & \gamma s_\beta \\ s_\alpha & s_\beta + g + 1 \end{bmatrix} \begin{bmatrix} k_\alpha^S \\ k_\beta^S \end{bmatrix} = X \begin{bmatrix} 1 - r_\alpha \\ 1 - r_\beta \end{bmatrix}$$

The determinant of the matrice is:

$$A\,(s_\alpha, s_\beta, g) = (s_\alpha + g + 1)\,(s_\beta + g + 1) - \gamma s_\alpha s_\beta$$

It is strictly positive so there is a unique solution of the system. And finally, some calculations lead to:

$$k_\alpha^S = X\frac{1}{A}\left[(g+1)(1-r_\alpha)+s_\beta\frac{\delta-\Delta}{v-c_\alpha}\right] \quad (9)$$

$$k_\beta^S = X\frac{1}{A}\left[(g+1)(1-r_\beta)+s_\alpha(r_\alpha-r_\beta)\right] \quad (10)$$

And for generalist firms:
Individual quantity of baseload capacity can be obtained with the relation $(1-\gamma)k_\alpha^G = k_\alpha^S-\gamma k_\beta^S$ by noting that $(1-r_\alpha)-\gamma(1-r_\beta)=(1-\gamma)(1-r)$.
And the peak capacity is simply $k_\beta^S-k_\alpha^G$.

$$k_\alpha^G = X\frac{g}{A}\left[(g+s_\beta+1)(1-r)-s_\alpha(r-r_\alpha)\right] \quad (11)$$

$$k_\beta^G = X\frac{g}{A}\left[(g+s_\alpha+1)(r-r_\beta)-s_\beta(1-r)\right] \quad (12)$$

So if there is an equilibrium with generalist firms that invest in strictly positive quantities of both type of capacities the equilibrium quantities are defined by equations (9), (10) and for generalist firms by (11) and (12).

Furthermore, if $s_\alpha(r-r_\alpha)\leq(g+s_\beta+1)(1-r)$ and $s_\beta(1-r)\leq(g+s_\alpha+1)(r-r_\beta)$ quantities defined by these equations described equilibrium strategies: each firm's profit is concave and maximimum at these quantities.

2. Let assume that generalist firms only invest in peak capacities at equilibrium.

Equilibrium quantities can be found from above calculations by replacing s_β by $g+s_\beta$ and g by 0.

So if such an equilibrium exists, it is fully described by quantities:

$$\begin{aligned}
k_\alpha^S &= X\frac{1}{A(s_\alpha,s_\beta+g,0)}\left[1-r_\alpha+(s_\beta+g)\frac{\delta-\Delta}{v-c_\alpha}\right]\\
k_\beta^S &= X\frac{1}{A(s_\alpha,s_\beta+g,0)}\left[1-r_\beta+s_\alpha(r_\alpha-r_\beta)\right]\\
k_\alpha^G &= 0 \text{ and } k_\beta^G=k_\beta^S
\end{aligned}$$

These quantities described an equilibrium only if generalist firm has an incentive not to invest in baseload capacity. And it is the case if the aggregate baseload capacity is above the first best optimal quantity: $s_\alpha k_\alpha^S > k_\alpha^* = X(1-r)$ and this inequality is equivalent to:

$$s_\alpha \geq (g+s_\beta+1)(1-r)/(r-r_\alpha)$$

3. Let assume that generalist firms only invest in baseload capacities at equilibrium.

If at equilibrium generalist firms only invest in baseload capacity equilibrium strategies are:

$$\begin{aligned}
k_\alpha^S &= X\frac{1}{A\left(s_\alpha+g,s_\beta,0\right)}\left[1-r_\alpha+s_\beta\frac{\delta-\Delta}{v-c_\alpha}\right]\\
k_\beta^S &= X\frac{1}{A\left(s_\alpha+g,s_\beta,0\right)}\left[1-r_\beta+\left(s_\alpha+g\right)\left(r_\alpha-r_\beta\right)\right]\\
k_\alpha^G &= k_\alpha^S \text{ and } k_\beta^G=0
\end{aligned}$$

These quantities described an equilibrium only if the aggregate quantity of peak capacity is above the first best quantity. It is so if and only if:

$$s_\beta \leq \left(g+s_\alpha+1\right)\left(r-r_\beta\right)/\left(1-r\right)$$

Propositions 1 and 2 are directly obtained from these results.

B Quantities of capacity derivatives

I establish expressions of quantities derivatives with respect to the number of firms s_α and s_β. When there are only specialized firms first order conditions are:

$$\begin{aligned}
\left(s_\alpha+1\right)k_\alpha^S+\gamma s_\beta k_\beta^S &= X(1-r_\alpha)\\
s_\alpha k_\alpha^S+\left(s_\beta+1\right)k_\beta^S &= X(1-r_\beta)
\end{aligned}$$

- Derivatives of quantities with respect to s_β :

By derivation of first order conditions with respect to s_β :

$$\begin{aligned}
\left(s_\alpha+1\right)\frac{\partial s_\alpha k_\alpha^S}{\partial s_\beta}+s_\alpha\gamma\frac{\partial s_\beta k_\beta^S}{\partial s_\beta} &= 0\\
s_\beta\frac{\partial s_\alpha k_\alpha^S}{\partial s_\beta}+\left(s_\beta+1\right)\frac{\partial s_\beta k_\beta^S}{\partial s_\beta} &= k_\beta^S
\end{aligned}$$

This leads to the following expressions of derivatives:

$$\frac{\partial s_\alpha k_\alpha^S}{\partial s_\beta}=-\frac{s_\alpha}{A}\gamma k_\beta^S \text{ and } \frac{\partial s_\beta k_\beta^S}{\partial s_\beta}=\frac{s_\alpha+1}{A}k_\beta^S$$

And concerning aggregate quantity of capacity:

$$\frac{\partial k^S}{\partial s_\beta} = \frac{\partial s_\alpha k_\alpha^S}{\partial s_\beta} + \frac{\partial s_\beta k_\beta^S}{\partial s_\beta} = \frac{1}{A} k_\beta^S \left[1 + s_\alpha \left(1-\gamma\right)\right]$$

- Derivatives of quantities with respect to s_α :

From first order conditions:

$$\begin{aligned} \left(s_\alpha + 1\right) \frac{\partial s_\alpha k_\alpha^S}{\partial s_\alpha} + s_\alpha \gamma \frac{\partial s_\beta k_\beta^S}{\partial s_\alpha} &= k_\alpha^S \\ s_\beta \frac{\partial s_\alpha k_\alpha^S}{\partial s_\alpha} + \left(s_\beta + 1\right) \frac{\partial s_\beta k_\beta^S}{\partial s_\alpha} &= 0 \end{aligned}$$

This give the expression of quantities evolution with respect to the number s_α :

$$\frac{\partial s_\alpha k_\alpha^S}{\partial s_\alpha} = \frac{s_\beta + 1}{A} k_\alpha^S \text{ and } \frac{\partial s_\beta k_\beta^S}{\partial s_\alpha} = -\frac{s_\beta}{A} k_\alpha^S$$

And the derivative of the aggregate quantity:

$$\frac{\partial k^S}{\partial s_\alpha} = \frac{\partial s_\alpha k_\alpha^S}{\partial s_\alpha} + \frac{\partial s_\beta k_\beta^S}{\partial s_\alpha} = \frac{1}{A} k_\alpha^S$$

C Proof of proposition 3

I relax the integer constraint and consider the effect of change of s_β on welfare. Partial derivatives of welfare with respect to k_α and k_β are:

$$\begin{aligned} \frac{\partial W}{\partial k_\alpha} &= \frac{v - c_\alpha}{X}(X - k) - I_\alpha + \delta k_\beta \\ \frac{\partial W}{\partial k_\beta} &= \frac{v - c_\beta}{X}(X - k) - I_\beta \end{aligned}$$

Injecting first order conditions give the following expression for derivative of welfare with respect to s_β:

$$\frac{dW}{ds_\beta} = \frac{v - c_\alpha}{X} k_\alpha^S \frac{\partial k_\alpha^S}{\partial s_\beta} + \frac{v - c_\beta}{X} k_\beta^S \frac{\partial k_\beta^S}{\partial s_\beta}$$

Injecting the expressions of capacities derivatives into above formula and factorizing gives:

$$\frac{dW}{ds_\beta} = \left(v - c_\beta\right) k_\beta^S \left[\left(s_\alpha + 1\right) k_\beta^S - k_\alpha^S\right] / AX$$

It is unclear whether welfare is concave or not (it is not in general) but it is quasi concave because its derivative is null only once and strictly positive (resp. negative) for smaller (resp. greater) values of s_β. I establish it directly by injecting formula of equilibrium quantities:

$$\begin{aligned} A\left[(s_\alpha+1)\,k_\beta^S-k_\alpha^S\right]/X &= (s_\alpha+1)\left[1-r_\beta+s_\alpha\left(r_\alpha-r_\beta\right)\right] \\ &\quad -s_\alpha\left[1-r_\alpha+s_\beta\left(\delta-\Delta\right)/\left(v-c_\alpha\right)\right] \end{aligned}$$

As this expression is decreasing with respect to s_β welfare is quasi concave. Furthermore it is maximum at:

$$s_\beta^* = \frac{1}{s_\alpha}\frac{v-c_\alpha}{\delta-\Delta}\left[(1-r_\alpha)+(s_\alpha+1)^2\left(r_\alpha-r_\beta\right)\right]$$

D Proof of proposition 4

The analysis is similar to the previous one. I relax the integer constraint and consider the effect of a change of s_α on welfare. The derivative of welfare with respect to s_α :

$$\frac{dW}{ds_\alpha} = \frac{v-c_\alpha}{X}k_\alpha^S\frac{\partial s_\alpha k_\alpha^S}{\partial s_\alpha}+\frac{v-c_\beta}{X}k_\beta^S\frac{\partial s_\beta k_\beta^S}{\partial s_\alpha}$$

Injecting the expressions of capacities derivatives into above formula and factorizing gives:

$$\frac{dW}{dn} = (v-c_\alpha)\,k_\alpha^S\left[(s_\beta+1)\,k_\alpha^S-\gamma s_\beta k_\beta^S\right]/AX$$

Injecting formula of equilibrium quantities:

$$\begin{aligned} \left[(s_\beta+1)\,k_\alpha^S-\gamma s_\beta k_\beta^S\right]/X &= 1-r_\alpha+s_\beta\left(s_\beta+2\right)\left(\delta-\Delta\right)/\left(v-c_\alpha\right) \\ &\quad -s_\beta s_\alpha\left(r_\alpha-r_\beta\right)\gamma \end{aligned}$$

As this expression is decreasing with respect to s_α welfare is quasi concave and maximum at:

$$s_\alpha^*(s_\beta) = \frac{1}{s_\beta}\frac{1}{\left(r_\alpha-r_\beta\right)}\left[(1-r_\beta)+(s_\beta+1)^2\,\frac{\delta-\Delta}{v-c_\beta}\right]$$