# Strategic Investment and Spot Market Design in Electricity Markets*

Veronika Grimm† — University of Erlangen–Nuremberg

Gregor Zoettl‡ — University of Munich

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**Abstract**

In liberalized electricity markets strategic firms compete in an environment characterized by fluctuating demand and non–storability of electricity. While spot market design under those conditions by now is well understood, a rigorous analysis of investment incentives is still missing. Existing models, as the peak–load–pricing approach, analyze welfare optimal investment and find that optimal investment is higher with more competitive spot markets. In this paper we propose a multistage game with *strategic* firms that anticipate competition on many consecutive spot markets with fluctuating (and possibly uncertain) demand. We study how the degree of spot market competition affects investment incentives and welfare, and provide an application of the model to electricity market data. Our results show that more competitive spot market prices decrease investment incentives of *strategic* firms and may even lead to a welfare reduction. Our analysis demonstrates that the Peak Load Pricing approach cannot be used to "approximate" investment incentives of strategic firms since it does not correctly capture the impact of spot market competition on the investment incentives of strategic players.

**Keywords:** Strategic investment, demand fluctuation, cost fluctuation, non–storable goods, electricity market design, market power, spot market competition.
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†Friedrich–Alexander–Universität Erlangen–Nürnberg, Department of Economics, Lange Gasse 20, D–90403 Nürnberg, Germany, veronika.grimm@wiso.uni-erlangen.de

‡Ludwig-Maximilians-Universität München , Seminar für Wirtschaftstheorie, Ludwigstrae 28, 80539 München, gregor.zoettl@lrz.uni-muenchen.de

# 1 Introduction

Incentives to invest in generation capacity have been heavily debated in the recent literature on electricity market regulation. Many authors suspect that there is a trade–off between low spot market prices and proper investment incentives if firms behave strategically. As Paul Joskow (2008) puts it, "policymakers in many countries are concerned that competitive wholesale markets for electricity do not provide adequate incentives for investment in sufficient quantities of generating capacity."

A thorough analysis of investment incentives in electricity markets, however, is still missing — but it is crucial for regulatory policy and electricity market design. In this paper we provide a model to analyze investment incentives of strategic firms prior to spot market competition. We illustrate how different spot market rules affect investment incentives and welfare, and provide an application of the model to electricity market data.

Let us first briefly illustrate why existing models do not capture investment incentives in liberalized elecricity markets accurately. First, the seminal result of Kreps and Scheinkman (1983) (in a nutshell, if firms can choose their capacities prior to their production decision, price and quantity competition lead to equivalent market outcomes) does not apply to the case of electricity markets, for the following reason. Electricity is not storable and supply has to match (fluctuating) demand at any point in time.[1] Thus, the analysis of investment incentives has to account for the fact that almost always either a fraction of capacity will run idle or capacity is not sufficient. Capacity constraints only affect prices in the latter case, whereas if capacity is sufficient spot market rules determine the price.[2] Consequently, in the presence of demand fluctuations it is just impossible to predetermine spot market outcomes in every state of the world by a capacity choice.

For the case of regulated monopoly, the peak load pricing literature already analyzed the investment problem. Since the liberalization of electricity markets all over the world, however, strategic firms have interacted on those markets within a regulatory framework that affects production and investment incentives. Still, in the applied literature on electricity markets, the peak–load–pricing approach is often used in order to "approximate" investment incentives of strategic firms. Our paper will show, however, that such an approximation yields exactly the wrong policy conclusions: While welfare optimal investment (as derived by the peak load pricing approach) is higher if spot markets are more compet-

[1] Notice that the type of questions we analyze (the main feature is non-storability of the good) is relevant also for a series of other markets. Examples are oil and gas extraction, capacity choices of hotels and hospitals (e.g. number of beds), or capacity choices of airlines (number of planes), etc. Our main motivation for this paper was, however, to get a deeper understanding investment incentives in electricity markets, an issue which is not yet well understood for liberalized electricity markets.

[2] And, moreover, spot market rules determine when exactly the capacity bound is met.

itive, strategic firms invest less if they expect a more competitive spot market outcome. The reason is that strategic firms will sidestep a tight spot market regulation by lower investment which allows them to make high profits when prices are demand-driven because of insufficient capacity.[3]

As we have argued, a proper understanding of investment incentives of *strategic* firms is crucial for the evaluation of different electricity wholesale market designs. However, studying investment incentives of strategic firms that have to decide on their capacities prior to competing on many consecutive spot markets requires analysis of a complicated multistage game. In our approach we assume that investment takes place at a first stage prior to competition at the spot markets. Firms anticipate fluctuating spot market demand (and also production cost) and, moreover, upon investment they might be uncertain about the precise pattern of such fluctuations. When firms compete at the spot markets (day ahead at the power exchange) it seems plausible to assume that they have pretty good information on demand and production cost (i.e. uncertainty unraveled). A crucial choice in our framework is how to model short run spot market competition. We therefore discuss this issue in some detail in the following paragraph.

Actually, most of the research on electricity markets has focused on short run performance. As Joskow (2008) states, "we now understand how to design wholesale electricity markets that work well in the short run." One of the most common approaches to think about competition at electricity spot markets is based on the concept of supply function competition developed by Klemperer and Meyer (1989) and applied to the case of electricity markets by Green and Newbery (1992). The range of equilibria generated by this approach is bounded below by the competitive market outcome and above by the Cournot solution.[4] Which of the equilibria is being played in a particular market likely depends on specific market rules and institutions. As Borenstein et al. (2008) put it: "To the extent that market rules and local regulatory differences influence market outcomes by helping determine which of the many possible equilibria arise, these impacts can be thought of as placing the market price within these bounds." In a dynamic investment game a continuum of equilibria at the production stage implies very imprecise overall equilibrium predictions ranging up to the collusive outcome (folk theorems). In order to obtain meaningful solu-

[3]Notice that fluctuations of either demand or supply do not pose much problems in the case of storable output. Then capacity has to be sufficient to serve total demand in all markets on average, a situation which can well be captured by well known frameworks of deterministic capacity choice such as the prominent contribution by Kreps and Scheinkman and its follow up literature. It is crucial to notice, however, that those findings do not apply to the case of non-storable products. In this case exact demand patterns are crucial for investment incentives.

[4]Especially when uncertainty regarding demand at each single spot market is small, the Cournot and the competitive solution are indeed the lowest and the highest equilibrium.

tions for the strategic investment game we will thus limit our analysis to those two extreme cases, the Cournot and the competitive solution.[5] This approach will allow us to address the central questions of this paper:

1. How does spot market design influence firms' investment decisions?
2. And (how) does this answer depend on the precise modeling of investment choices (strategic investment versus optimal investment as modeled in the peak load pricing literature)?

Let us briefly summarize our results. We establish existence and (where possible) also uniqueness of equilibrium of the strategic investment game for both regimes of spot market competition (Cournot and competitive prices). We then show that the lower bound of the above mentioned range of spot market equilibria (the case of perfect competition, which is clearly more desirable from a short run perspective) is potentially less desirable in the long run. A competitive spot market leads to strictly lower investment by strategic firms and might even lead to a welfare reduction. In a model with free entry (where firms enter the market as long as they expect to cover some fixed cost of entry) a competitive spot market is even less desirable since it gives rise to a lower number of active firms in the market. In the empirical part of the paper we quantify the effects we identified in the theoretical part using data of the German electricity market.

We also compare the results we obtain for strategic firms with the results obtained in a framework where optimal investment is derived, as it is typically done by applied studies on the investment problem.[6] We obtain exactly the opposite result: if firms are not modeled as strategic players a competitive spot market is more desirable both, from a short run and from a long run perspective. Our results demonstrate that it is crucial to explicitly model strategic interaction at the investment stage. Our empirical analysis reveals that the impact on welfare and capacity level is drastic.

Let us finally review some of the related literature. The traditional investment literature focused on the case of optimal (instead of strategic) investment decisions. The peak load pricing literature was initiated by Steiner (1957) and Boiteux (1960) and is extensively reviewed by Crew and Kleindorfer (1986) and Crew et al. (1995). In a recent contribution Joskow and Tirole (2007) show how those results can also be extended to the case of perfectly competitive markets.

[5] One could additionally consider specifications of the supply function game that yield unique equilibria, as in Kühn (XXXX) or Holmberg (2008). Those scenarios would yield less investment than the case of Cournot competition at the spot markets, but more investment than the case of competitive behavior.

[6] See, for example, Boccard (2009), Bushnell (2005), Cramton and Stoft (2005), or Joskow (2007).

Two papers have analyzed strategic investment prior to a Cournot spot market. For the case of a linear duopoly Gabszewicz and Poddar (1997) show existence of a symmetric equilibrium. Murphy and Smeers (2005) characterize equilibrium investment in the very same linear duopoly setting, but allow for an asymmetric cost structure of the firms. The relationship between spot market design and firms' investment decisions has not been touched in those contributions, however.

As already mentioned above, there has been an intense debate of the question which framework is best suited in order to model competition at electricity spot markets. Whereas Green and Newbery (1992) proposed the supply function approach, an auction model was proposed by von der Fehr and Harbord (1993). Recently, Reynolds and Wilson (2000), Fabra and de Frutos (2006), and Fabra, Fehr and de Frutos (2008) have analyzed strategic investment incentives in a duopoly prior to an auction-like spot market with price competition. They show non-existence of symmetric equilibria (Reynolds and Wilson), and characterize some of the asymmetric equilibria for the duopoly case (Fabra and coauthors). It probably remains an unsolved question whether the supply function or the auction approach models spot market competition more accurately. However, the analysis of investment incentives prior to auction markets seems to be plagued by the lack of existence results (of symmetric equilibira) and by multiplicity of asymmetric ones. This makes policy evaluations or an analysis of the relationship of investment incentives and spot market design rather difficult.

Finally, departing from the perspective of optimal investment, as analyzed in the peak load pricing literature, towards an analysis of strategic investment behavior requires not only to account for the quantities that the firms invest, but also strategic timing of investment decisions may be an important issue. All above mentioned contributions (including this paper) exogenously fix a point in time when firms make their investment choices and focus exclusively on capacity levels chosen. In contrast, the "real option approach" analyzes the optimal timing of investment. Demand evolves according to a stochastic process (typically a Brownian motion) and firms decide when to adjust their investment to increased demand levels. This literature has been initiated by Dixit and Pindyk (1994), and has been applied to strategic games by Baldursson (1998) or Grenardier (2002). In order to keep those models tractable, however, the authors typically assume that the entire capacity is being used for production (the case that firms are unconstrained cannot occur). That is, by assumption spot markets are not modeled and shifting levels of demand have to be interpreted as movements of average demand in the long run.

Our paper is organized as follows: In section 2 we state the model. Section 3 contains the theoretical analysis and results. We consider strategic investment in section 3.1 and welfare optimal investment in section 3.2. In section 3.3 we provide a comparison of investment levels in the scenarios we consider and show that the strategic approach reverts the policy conclusion. Section 4 contains an empirical analysis, where we also discuss the welfare implications of spot market regulation. Section 5 concludes.

## 2 The Model

We analyze an investment game where firms choose capacities anticipating demand and cost fluctuations, and thereafter make output choices at a series of spot markets. We denote by $q = (q_1, \ldots, q_n)$ a vector of outputs of the $n$ firms at a spot market, and by $Q = \sum_{i=1}^{n} q_i$ total quantity produced at that spot market.

Inverse demand in spot market $\theta$ is given by the function $P(Q, \theta)$, which depends on $Q \in \mathbb{R}^+$, and the random variable $\theta \in \mathbb{R}$ which represents the different demand scenarios. All firms face the same cost function for each $\theta \in \mathbb{R}$, which we denote by $C(q_i, \theta)$. The random variable $\theta \in \mathbb{R}$ is distributed according to a distribution $F(\theta)$, which specifies relative frequencies of different demand realizations.

Remark 1 (Why a Continuum of Spot Markets?) *We choose a continuum of spot markets, which could be motivated in two different ways: First, firms bid for 8760 hours each year and installed capacity serves for more than ten years. Thus, a continuum might be an appropriate approximation. Second, also demand uncertainty might play a role since firms typically cannot predict all future demand realizations exactly. This scenario would certainly suggest a continuous framework and is also covered by our analysis.*

We introduce the parameter $z \leq 0$ as a lower bound on market prices in order to take into account nonnegativity of prices ($z = 0$) or disposal cost ($z < 0$). We denote the quantity where this lower bound is met by $\overline{Q}(\theta)$.[7] The following two assumptions on demand and cost for each realization of the demand parameter $\theta \in \mathbb{R}$ have to be satisfied only for quantities $0 \leq q_i \leq Q < \overline{Q}(\theta)$.

Assumption 1 (Assumptions at each $\theta$) *(i) Inverse demand $P(Q, \theta)$ is twice continuously differentiable*[8] *in $Q$ with $P_q(Q, \theta) < 0$ and $P_q(Q, \theta) + P_{qq}(Q, \theta) q_i < 0$.*

*(ii) $C(q_i, \theta)$ is twice continuously differentiable in $q_i$ with $C_q(q_i, \theta) \geq 0$ and $C_{qq}(q_i, \theta) \geq 0$.*

[7]In case the lower bound is not binding we can set $\overline{Q}(\theta) = \infty$. In order to ensure a bounded solution we then have to assume $\lim_{Q \to \infty} P(Q, \theta) < C_q(0, \theta)$ for each $\theta \in (-\infty, \infty]$.

[8]Throughout the paper we denote the derivative of a function $g(x, y)$ with respect to the argument $x$, by $g_x(x, y)$, the second derivative with respect to that argument by $g_{xx}(x, y)$, and the cross derivative by $g_{xy}(x, y)$.

Assumption 2 (Monotonicity Assumptions regarding $\theta$) *(i) $P(Q,\theta)$ and $C(q_i,\theta)$ are differentiable in $\theta$, and it holds that $P_\theta(Q,\theta) - C_{q\theta}(q_i,\theta) > 0$.*[9]

*(ii) $P(Q,\theta)q_i - C(q_i,\theta)$ is (differentiable) strict supermodular in $q_i$ and $\theta$, i. e. $P_\theta(Q,\theta) - C_{q\theta}(q_i) + P_{q\theta}(Q,\theta)q_i > 0$.*

The situation we want to analyze is captured by the following dynamic investment game. At the investment stage firms simultaneously build up capacities $x = (x_1, \ldots, x_n)$. Capacity choices are observed by all firms. Cost of investment $K(x_i)$ is the same for all firms and satisfies

Assumption 3 (Investment Cost) *Investment cost $K(x_i)$ is twice continuously differentiable, with $K_x(x_i) \geq 0$ and $K_{xx}(x_i) \geq 0$.*

Facing the capacity constraints inherited from the investment stage, firms simultaneously choose outputs at a sequence of spot markets with fluctuating demand levels. Since demand in a particular scenario $\theta$ is known prior to the output decision, produced quantities depend on the respective demand scenarios.

Finally, we state firm $i$'s profit from operating if capacities are given by $x$ and firms plan to choose feasible[10] production schedules $q(\theta)$ for all $\theta \in [-\infty, \infty]$.

$$\pi_i(x,q) = \int_{-\infty}^{\infty} \left[P\left(Q\left(\theta\right),\theta\right) q_i\left(\theta\right) - C\left(q_i\left(\theta\right),\theta\right)\right] dF\left(\theta\right) - K\left(x_i\right). \tag{1}$$

Throughout the paper we consider only cases where investment is gainful, i.e. $\int\limits_{-\infty}^{\infty} [P(0,\theta) - C(0,\theta)]dF(\theta) > K(0)$. Note that if the condition does not hold, no firm invests in capacity.

# 3 Results

In this section we analyze the investment game where firms simultaneously invest in capacity anticipating spot market competition in a series of markets with fluctuating demand. In

[9]Notice that demand and cost fluctuations in principle can be distinct processes. Then the parameter $\theta$ represents all joint realizations, which have to satisfy assumption 2. This requirement imposes some further restrictions on the model if cost and demand fluctuations should be considered simultaneously. Consider, for example, a model with linear demand $P(Q,\beta) = \beta - bQ$ and fluctuating but constant marginal cost $c(\gamma)$. For ease of exposition let both, $\beta$ and $\gamma$ follow a discrete distribution. Now sort all joint realizations $(\beta,\gamma)$ such that $\beta - c(\gamma)$ is increasing and index each realization by $\theta$. Observe that the resulting system satisfies assumption 2 (i) and 2 (ii). Thus, the model can deal simultaneously with cost and demand fluctuations in the case of linear demand, which we exploit in the empirical part of the paper. In case of non–linear demand it is more plausible to think about demand and cost fluctuations separately.

[10]That is, $0 \leq q_i(\theta) \leq x_i$ for all $\theta \in [-\infty, \infty]$, $i = 1, \ldots, n$.

order to be able to assess the impact of market power and of market design on investment incentives and production, we analyze four different scenarios.

In section 3.1 we consider the case that *strategic* firms choose *profit maximizing* investment levels. In this context we consider two extreme scenarios, the case of anticipation of high spot market prices (Cournot) as well as the case of competitive pricing (which may be a result of regulatory intervention[11] or just the result of competitive supply function bidding).

In section 3.2 we analyze the investment game assuming that socially optimal investment levels are chosen by the firms (i.e. we analyze unstrategic investment choice), and again consider the case of anticipation of high spot market prices as well as the case of competitive pricing at the spot market. The latter case coincides with the "competitive benchmark" that has been analyzed in the peak load pricing literature. On the one hand, an analysis of welfare optimal capacity levels yields insights on capacity levels that a social planer would like to implement. Comparison with strategic capacity choices as analyzed in section 3.1 reveals, moreover, that the policy conclusion is reverted when the analysis does not account for the incentives of *strategic* firms at the investment stage.

## 3.1 Strategic Investment

Consider the market game where firms strategically choose capacities as to maximize profits. Our first theorem shows that the investment game where firms engage in Cournot competition at the spot markets (SH — Strategic firms, High spot market prices) has a unique and symmetric equilibrium. If, however, firms anticipate competitive prices at the spot market (SL — Strategic firms, Low spot market prices), the investment game has multiple symmetric but no asymmetric equilibria.

THEOREM 1 (STRATEGIC CAPACITY CHOICE) *Suppose firms choose their capacities strategically.*

*(SH) If firms anticipate high spot market prices (Cournot competition) at the spot markets, the investment game has a unique equilibrium which is symmetric.*

*(SL) Suppose that firms anticipate competitive pricing at the spot markets, and that $C_q(q, \theta)$ is constant in $q$. Then, there exists at least one symmetric equilibrium, but there may be more than one. No asymmetric equilibria exist.*

[11] We are aware that regulation down to spot market prices requires a lot of information on the part of the social planer. Although stylized, however, it allows detailed insights in what happens to investment incentives should the regulator succeed in implementing competitive prices at the spot market.

*Total equilibrium investment in scenario SD, $D \in \{H, L\}$, $X^{SD}$, solves*

$$\int_{\tilde{\theta}^D(X^{SD})}^{\infty} \left[ P\left(X^{SD}, \theta\right) + P_q\left(X^{SD}, \theta\right) \frac{X^{SD}}{n} - C_q\left(\frac{X^{SD}}{n}, \theta\right)\right] dF(\theta) = K_x\left(\frac{X^{SD}}{n}\right),$$

*where $\tilde{\theta}^D\left(X^S\right)$ is the demand scenario from which on firms are capacity constrained at the spot market.*[12]

PROOF See appendix B □

Let us emphasize some important aspects of our results. First, we could show that *under standard regularity assumptions* the investment game has a *unique* equilibrium if firms expect Cournot competition at the spot markets. Second, we find that equilibrium investment can be characterized by a rather intuitive condition. The condition simply says that marginal profit generated by an additional unit of capacity (at the spot markets) must equal marginal cost of investment. When calculating the marginal profit generated by an additional unit of capacity, however, one has to take into account that additional capacity affects a firm's profit only in those states of nature where capacity is binding. Thus, only those spot markets are taken into account where firms are indeed capacity constrained, i. e. only the interval $[\tilde{\theta}^D\left(X^{SD}\right), \infty]$ is relevant, not the whole domain of $\theta$.

Note that the critical demand scenario $\tilde{\theta}$ (from which on firms are capacity constrained) depends on the degree of market power at the spot markets. If firms strategically withhold production at the spot market (as under Cournot competition) the critical demand scenario is higher than in the case where they behave competitively. Observe that actually the market game at the spot markets enters into the first order condition solely through the critical demand realization.

If firms anticipate competitive behavior at the spot markets, existence and uniqueness of a symmetric equilibrium cannot be shown in the general case (part (SL) of the theorem). Only for constant marginal production cost we obtain existence (but not uniqueness).[13] An immediate insight of this result is that regulatory intervention at the spot market (that forces prices below the Cournot level) may lead to high strategic uncertainty for the firms. Later in section 3.3 we will show that, moreover, investment incentives are lower if firms anticipate competitive prices at the spot market than in the case where they anticipate Cournot competition.

[12] I.e. $\theta^H(X^{SH})$ is implicitly defined by $P(X^{SH}, \tilde{\theta}^H) + P_q(X^{SH}, \tilde{\theta}^H)\frac{X^{SH}}{n} = C_q(\frac{X^{SH}}{n}, \tilde{\theta}^H)$ and $\theta^L(X^{SL})$ is implicitly defined by $P(X^{SL}, \tilde{\theta}^L) = C_q(\frac{X^{SL}}{n}, \tilde{\theta}^L)$, respectively.

[13] The basic problem is that in neither case the profit is quasiconcave, which makes standard analysis impossible. In the case of linear marginal cost, however, we can exploit recent insights on oligopolistic competition that makes use of lattice theory (Amir (1996) and Amir and Lambson (2000)). In the general case (i. e. strictly convex production cost), however, the game cannot be reformulated as a supermodular game and thus, even those more sophisticated techniques do not help.

## 3.2 Optimal Investment

In this section we characterize investment levels that are optimal from a welfare point of view — again for a Cournot and a competitive spot market market outcome. The analysis is interesting for two reasons: First, from a comparison with the results of section 3.1 we learn how a social planer would like to influence the capacity choices of strategic firms. Second, the analysis reveals that the traditional approach (which does not account for strategic investment) predicts higher investment prior to competitive spot markets, while strategic firms actually invest less if the spot market is more competitive.

Optimal investment in cases $WH$ (Welfare optimal investment at High spot market prices) and $WL$ (Welfare optimal investment at Low spot market prices) is characterized in the following theorem.

Theorem 2 (Welfare Maximization at Stage One) *Welfare maximizing industry capacity choices are unique and symmetric. Socially optimal capacity in scenario $WD$, $D \in \{H, L\}$, $X^{WD}$, solves*

$$\int_{\tilde{\theta}^D(X^{WD})}^{\infty} \left[ P\left(X^{WD}, \theta\right) - C_q\left(\frac{1}{n}X^{WD}, \theta\right)\right] dF(\theta) = K_x\left(\frac{1}{n}X^{WD}\right), \tag{2}$$

*where $\tilde{\theta}^D\left(X^{WD}\right)$ is the demand scenario from which on firms are capacity constrained at the spot markets.*[14]

Proof See appendix C □

Note that also the characterization of welfare optimal investment levels is rather intuitive. The condition implies that in the welfare optimum capacity should be chosen such that expected marginal social welfare generated by an additional unit of capacity [LHS of (2)] should equal marginal cost of investment [RHS of (2)]. Again it is important to notice that only those scenarios are taken into account where firms are actually constrained *given the scheduled spot market production*, that is, over the interval $[\tilde{\theta}^D(X^{WD}), \infty]$. Note that for a given level of investment, firms are constrained earlier if they behave competitively at the spot markets, since under Cournot competition they withhold quantity at the spot markets in order to affect prices. Consequently, additional capacity is used more often and thus, contributes more to expected marginal welfare if the spot market behavior is more competitive. This implies that welfare maximizing capacity should be higher if the spot market is competitive than in case firms play the Cournot outcome. We show this formally in section 3.3.

[14] I.e. $\theta^H(X^{WH})$ is implicitly defined by $P(X^{WH}, \tilde{\theta}^H) + P_q(X^{WH}, \tilde{\theta}^H)\frac{X^{WH}}{n} = C_q(\frac{X^{WH}}{n}, \tilde{\theta}^H)$ and $\theta^L(X^{WL})$ is implicitly defined by $P(X^{WL}, \tilde{\theta}^L) = C_q(\frac{X^{WL}}{n}, \tilde{\theta}^L)$, respectively.

We finally point out that if firms do not act strategically, investment and production levels coincide with the socially optimal solution, again given the number of firms:

Remark 2 (Non-Strategic Firms) *If firms do not behave strategically (i. e. they act as price takers at the spot markets and ignore their impact on total capacity at the investment stage), the welfare maximizing market outcome ($WL$) is implemented.*

## 3.3 Comparison of Market Outcomes for Strategic versus Optimal Investment

In this section we compare equilibrium investment in the scenarios we analyzed in the previous two sections and discuss how the consideration of strategic (instead of welfare optimal) investment affects policy conclusions regarding the desirable spot market design. Our first result shows that the traditional approach (unstrategic investment) predicts higher investment for a more competitive spot market, while strategic firms would actually invest less if the spot market outcome is expected to be competitive.

Theorem 3 (Investment Levels) *(i) Non-strategic (welfare optimal) investment is higher if the spot market is more competitive, i. e. $X^{WL} \geq X^{WH}$.*

*(ii) Strategic firms invest less if the spot market is more competitive, i. e. $X^{SL} \leq X^{SH}$.*

Proof See appendix D □

Let us briefly provide some intuition for our result, using some characteristics of the first order conditions as stated in theorems 1 and 2. Let us first draw the reader's attention to the particular structure of the first order conditions. They all equalize expected marginal profit or welfare [LHS] with marginal cost of capacity [RHS]. Note that, at the LHS, the objective at the investment stage (either profit or welfare) is reflected only in the integrand. That is, we integrate over *marginal profit* in cases where the firms maximize profits at the investment stage ($SH$ and $SL$) and over *marginal welfare* in cases where welfare is the investment stage–objective ($WL$ and $WH$). The scenario at the spot market enters exclusively into the lower limit of integration, since the outcome of spot market competition affects the demand scenario from which on firms are constrained given the capacities chosen at the investment stage. Marginal profits or welfare once firms are constrained are not directly influenced by the spot market regime, since prices are demand–driven if capacity is at its bound.

Now consider the optimal capacity choice of strategic firms. If the firms anticipate Cournot competition at the spot markets, marginal profit generated by additional capacity is positive in each scenario where the firm is constrained. If firms expect competitive behavior at the spot market, however, this is not the case. A firm thus anticipates that it might be forced to use additional capacity although the marginal profit from using it may be negative.[15] Consequently, additional capacity is less valuable to the firms in the latter case and investments are lower if the spot market is more competitive.

In contrast, if capacity is chosen as to maximize social welfare, an additional unit of capacity has a positive impact whenever the spot market price is above marginal cost (which is always the case). As already mentioned, firms are constrained earlier if spot market behavior is more competitive. This implies that for any initial capacity level additional capacity is used more often if the spot market is competitive and therefore generates a higher increase in social welfare. Optimal investment must thus be higher for a competitive spot market than for the case of Cournot competition at spot markets.

We have demonstrated above that for any fixed capacity level, additional capacity is more valuable if welfare maximization is the objective (cases $W$) than in case the firms maximize profits (cases $S$), since expected marginal welfare is always higher than expected marginal profit.[16] An immediate result is that a social planer would always like to increase the investment of strategic firms above the chosen level (this is also shown formally in the proof of theorem 3).

Whereas capacities in the scenarios we analyze can be ranked unambiguously, this is not always true when it comes to social welfare. A welfare comparison is simple and straightforward for cases $SH$, $WH$, and $WL$ (where welfare is increasing in this order). In case firms choose their capacities strategically it is not obvious, however, whether welfare is higher in case of high (Cournot) or low (competitive) spot market prices (case $SH$ or $SL$). In scenario $SH$ firms exercise market power at the spot market, whereas in case $SL$ spot prices are at the competitive level. Thus, in absence of capacity constraints welfare would be higher in $SL$. However, at the investment stage strategic firms choose lower capacities in case $SL$ such that prices are higher in case $SL$ than in $SH$ whenever firms are capacity constrained in both cases. Consequently, a welfare comparison of the two cases is not straightforward and necessarily depends on details of the model's specification. A simplified model with linear demand demonstrates that both, an increase and a decrease in welfare is possible and suggests that competitive prices at spot markets are particularly undesirable from a welfare point of view if the number of firms is low. Thus, in particular if market power already is a serious problem (few firms, Cournot spot market outcome), a more competitive spot market reduces welfare even more. In markets with a higher number of firms, however, the scenario with low spot market prices ($SL$) yields slightly higher

[15] This is the case in all demand scenarios in $[\tilde{\theta}^{SL}, \tilde{\theta}^{SH}]$.

[16] Formally, at a fixed capacity level, the critical value $\tilde{\theta}$ is the same in both cases, but the integrand is pointwisely bigger in cases $W$ than in cases $S$.

welfare. We come back to this issue in section 4, where we fit our model to the data of the German electricity market. We obtain the following general results on welfare:

THEOREM 4 (WELFARE COMPARISON) *(i) If investment is chosen as to maximize welfare, implementation of a competitive spot market is always desirable, i.e.* $W^{WL} \geq W^{WH}$.

*(ii) If investment is chosen strategically, implementation of a competitive spot market is not always desirable, i.e. it may obtain that* $W^{SL} \leq W^{SH}$.

*(iii) If investment is chosen strategically, implementation of a competitive spot market is always less beneficial than in the case of welfare maximizing investment, i.e.* $\left(W^{WL} - W^{WH}\right) \geq \left(W^{SL} - W^{SH}\right)$.

PROOF See appendix E □

Theorem 4 shows that accounting for the fact that firms invest strategically (as compared to the consideration of unstrategic firms) may revert the predicted impact of spot market design on investment incentives and welfare. It rather seems essential to have a closer look at the particular market conditions in order to derive reliable welfare conclusions. As an example we conduct such an analysis for the German electricity market in section 4. There we illustrate how our model can be applied to get deeper insights on welfare and investment effects of different degrees of spot market competition in a particular market. Before we proceed to the empirical part, however, we address the issue of entry, which has been ignored in out analysis up to now. As it turns out, all our results continue to hold in a model with free entry at some given entry cost, which is stated in the following theorem.

THEOREM 5 (FREE ENTRY) *Suppose strategic firms can enter the market at some fixed cost $F$ in a free entry equilibrium. If firms expect a competitive spot market outcome, then (weakly) less firms will enter the market. The statements of theorems 3 and 4 remain valid also for the case of free entry.*

PROOF See appendix F □

# 4 An Empirical Analysis of Capacity Choice in Electricity Markets — The Example of Germany

In this section we demonstrate how our theoretical insights can be used to assess (long run) capacity and welfare effects of electricity market liberalization. We also quantify the capacity and welfare effects of several recent policy proposals for different degrees of market concentration.[17] The approach can be applied to any electricity market by fitting the theoretical model to the corresponding data and comparing predicted strategic capacity choices to the actually installed level.[18] Here, for the reason of data availability, we use data of the German electricity market.

Note that — although they are quite stylized — our scenarios capture nicely some recent policy proposals. A competitive spot market as described in case $SL$ is closely related to the common proposal to monitor tightly the firms' spot market behavior (in order to force prices down to the competitive level).[19] The difference of capacity levels in scenarios $SH$ and $WH$ is a proxy for the desirability of capacity markets or other mechanisms that increase investment incentives.[20] Thus, our analysis yields insights to assess some policy tools that have been at the focus of the current debate on the need of reorganization of electricity markets. Apart from capacity choices, we also focus on the price distribution in the different scenarios and on welfare implications of regulatory interventions.

Our aim is to fit the theoretical model as closely as possible to the data of the German Electricity market for the year 2006 and to compute resulting investment in gas turbine generation capacity for the scenarios SL, SH, WH, and WL. Note that this approach yields *total* investment under the assumption that each firm's *marginal* generating unit is always a gas turbine. Since investment in the last unit of capacity (which, of course, determines total capacity) is always a marginal decision, we do not need to specify the inframarginal technology mix for the empirical analysis. Note however, that we need to assume that firms are symmetric in size (but not necessarily with respect to their inframarginal technology mix). Since mark-ups in the Cournot model generally increase if firms become asymmetric, our results yield a lower bound for the extent of market power for a given number of firms.

In order to use our theoretical model for the analysis we chose to make the following specifications. We assume linear fluctuating demand $P(Q) = \theta - bQ$ and fluctuating but constant marginal cost $c(\theta)$. Note that for linear demand our model can allow simultaneously for both, demand and cost fluctuations. If we sort all realizations of demand and cost according to the differences $\theta - c(\theta)$, the resulting framework satisfies assumptions 1 to 3. Furthermore, for the sake of our applied example, we interpret the distribution over

[17] All welfare effects we demonstrate can also be shown in a simplified model with linear demand and uniform distribution of $\theta$. In particular, in Grimm and Zoettl (2007) we show that the more concentrated the market is, the less competitive the spot market outcome should be from a welfare point of view.

[18] We are not aware of any empirical studies of investment in electricity markets. The main reason presumably is that the post liberalization period is not yet long enough to generate data on investment cycles. This is also a strong argument for fitting a theoretical model to the primitives of a market to get an impression of possible long run effects that cannot appear in the data yet.

[19] See, e.g. Monopolkommission (2007), p.4, paragraph 9.*. If the regulator has perfect information, the result of such an intervention would be marginal cost pricing at the spot markets.

[20] Capacity markets have been proposed by Cramton and Stoft (2005), among others.

the demand scenarios as relative frequencies which have been accurately predicted by all firms.[21]

For a given demand and cost distribution and for given marginal investment cost, predicted capacities can be calculated by solving the corresponding first order conditions as stated in theorems 1 and 2. The resulting capacity choices allow us to derive the price distribution for those hours where capacity is binding, and to compare it to the observed price distribution. Moreover, we can capture the welfare effect of regulatory interventions and we can quantify the errors that would result from the consideration of non-strategic (instead of strategic) investment. To this aim we calculate the welfare difference to the case of strategic firms anticipating high spot market prices ($SH$) for scenarios $SL$, $WH$, and $WL$ and add up welfare differences generated in each hour of the year.

In order to assess the robustness of our results we do not perform the analysis for single parameter values, but rather for plausible ranges of parameter distributions. This concerns the following parameters of the model: The demand elasticity (determined by the slope of the demand function, $b$), marginal cost of production, $c$, and marginal investment cost, $k$. From the possible ranges of those parameters, our algorithm selects one random combination in each iteration. The resulting distributions of capacities and welfare differences give an impression of the sensitivity of our results to changes in the parameters. In the following we provide some details on the relevant ranges of our cost and demand parameters.

**Market demand:** To construct fluctuating market demand, we depart from hourly market prices (from the European Energy Exchange (EEX)[22]) and hourly quantities consumed (from the Union for the Co-ordination of Transmission of Electricity (UCTE)[23]) for the year 2006. We chose the value of $b$ in line with other studies on energy markets. Most studies that estimate demand for electricity[24] find short run elasticities between 0.1 and 0.5 and long run elasticities between 0.3 and 0.7.[25] The relevant range of prices is around $P = 100$ €/MWh and corresponding consumption is approximately $Q = 50$ GW. In our simulations we thus use a uniform distribution of $b$ on the interval $[0.004, 0.007]$, which corresponds to elasticities between 0.5 and 0.29.

[21] That is, in our empirical analysis we have no uncertainty but just demand fluctuation over time. In practice, there should be two competing effects if uncertainty would be added to the analysis. Since investment in gas turbines is rather risky and firms are typically risk averse, the benchmark determined should yield too much investment. On the other hand, however, our model implies that a risk neutral firm should invest more if risk is increased.

[22] See www.EEX.com

[23] See www.UCTE.org

[24] See, for example, Lijsen (2006) for an overview of recent contributions on that issue.

[25] E.g. Beenstock et al. (1999), Bjorner and Jensen (2002), Filippini Pachuari (2002), Booinekamp (2007), and many others.

**Production cost:** The major components of variable production cost are gas prices[26] and prices for $CO_2$ emission allowances.[27] The average TTF gas price in 2006 was 20 €/MWh and $CO_2$ permissions traded on average for 9.30 €/MWh.[28] The efficiency of gas turbines currently ranges at around $37,5\%$.[29] The resulting daily production cost for the year 2006 was on average 66.30 €/MWh. Daily values, as used in our empirical analysis, are illustrated in figure 1. In our simulations we use the observed distribution but multiply each realization by the factor $f$ which is uniformly distributed in [0.9, 1.1].

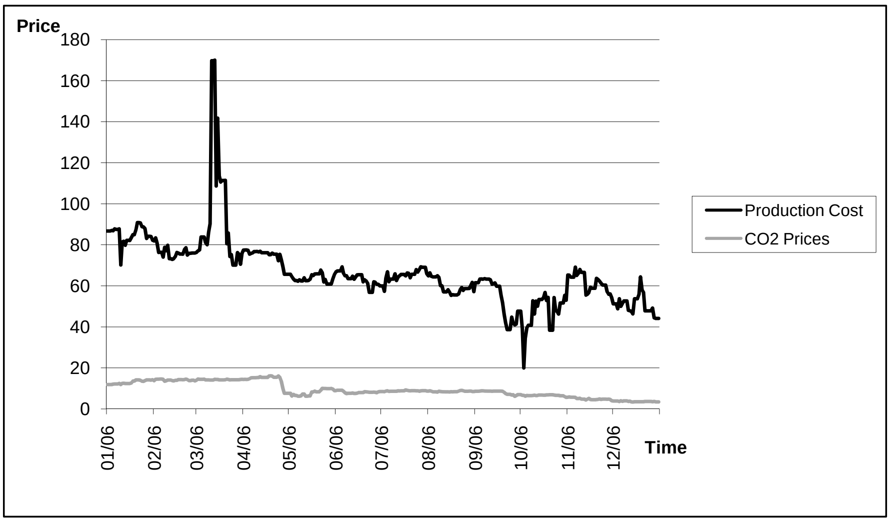


Figure 1: Production Cost in the Year 2006.

**Investment Cost:** Since we analyze investment incentives based solely on one year, we break down investment cost to annuities.[30] In order to take construction time of gas turbine plants into account we consider investment cost on the basis of data from the year 2000. We assume perfect foresight, i.e. all cost components have been predicted accurately by the firms at the time of their investment decision. We base investment cost on the following two studies: First, a study on the German energy market commissioned by the German

[26]Daily values from the Dutch Hub TTF, corrected for transportation cost.

[27]Daily data taken from the EEX. The emission-coefficient for natural gas is set by the German ministry of environment at 56t $CO_2$/TJ which corresponds to 0.2016t $CO_2/MWh$. Compare Umweltbundesamt (2004).

[28]Recall that we do not use the averages but the daily values in our simulation.

[29]See 2006 GTW Handbook or EWI and Prognos (2005).

[30]The results will thus only yield a benchmark for current profitability of investment. Provided, however, that yearly demand is increasing over time (and that strategic timing of investment is not an issue) our procedure should yield accurate predictions, even though once installed capacities cannot be removed the subsequent year.

Parliament (2002), with scenarios for investment decisions summarized in Weber and Swider (2004) [in the following GP/WS]. Second, Energiereport III, a study conducted by the Institute of Energy Economics (EWI) in Cologne and Prognos (2000) for the the German Ministry of Economics [in the following EWI/P].

The relevant annuity is determined as follows: Total investment cost ranges between 279 €/KW (GP/WS) and 300 €/KW (EWI/P). Annual fixed cost of running a gas turbine is already included in GP/WS, and is given by 8 €/KWa in EWI/P. This value is corrected by the average availability of gas turbines, which, in Germany, is given by 94%.[31] Based on a financial horizon of 20 years and an interest rate of 10 % this yields annuities of 34863 €/MWa (GP/WS) and 45998 €/MWa (EWI/P). Finally, the free allotment of $CO_2$ allowances granted to new power plants results in a de facto reduction of the annuity by the net value of the allocated allowances. Calculating their value on the basis of the average market price in 2006 yields 6305.3 €/MWa. The range of relevant annuities which we use in our simulation is consequently given by [28558, 39692] €/MWa.

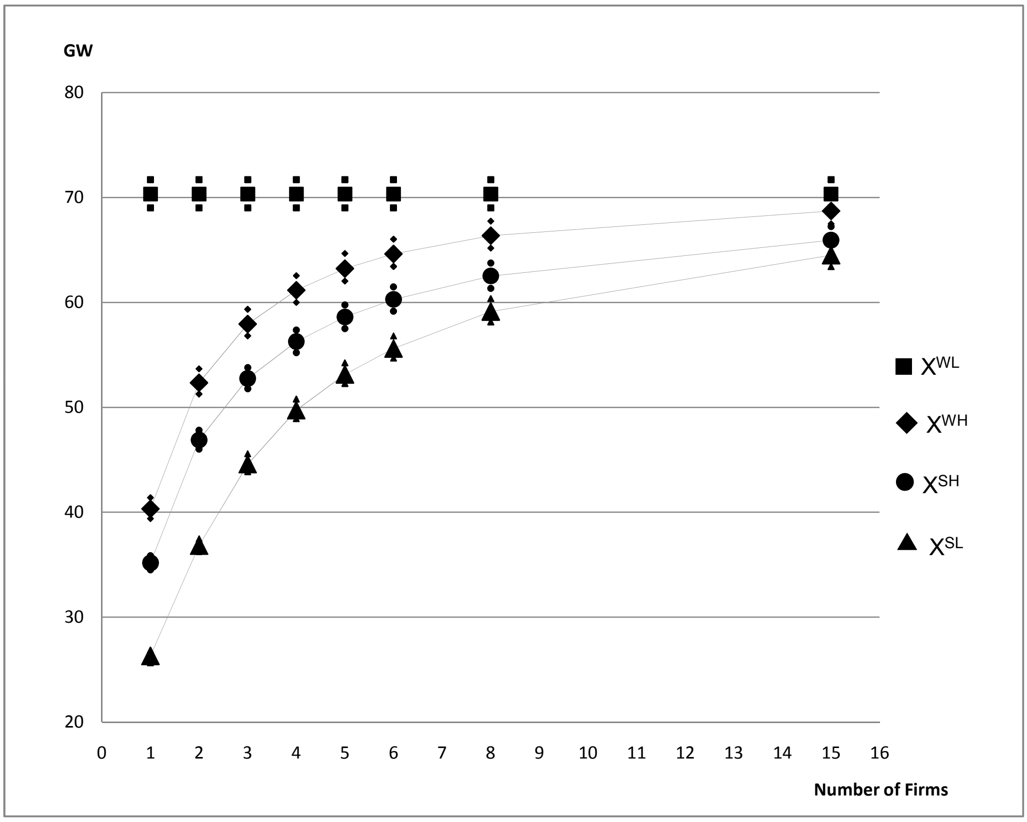


Figure 2: Investment Levels in all Four Cases.

[31] Compare VGB Powertech (2006).

Figure 2 shows — for different numbers of firms — total investment in all four scenarios we discuss. In the figure, the big symbols represent the average value while the two smaller symbols of the same type determine the 90 % confidence interval of our simulation. Obviously, predicted capacities are not very sensitive to changes in the parameters. The first best investment does not change in the number of firms since we assume that each firm's marginal generating unit is a gas turbine, independently of the number of firms and the level of demand. Strategic capacity choice prior to Cournot spot markets (scenario $SH$) is at only 50 % of the optimal level for the monopoly case, while it is at 80 % of the optimal level for four firms. The graph illustrates that the presence of market power not only affects spot prices, but also has a strong effect on capacity choices. Total capacity installed in Germany in 2006 was approximately 68 GW in a market with four large firms.[32] The relatively high level of actual capacity as compared to our results reflects the fact in the pre-liberalization period (i.e. before 1998) generators where subject to a rate of return regulation that imposed excessive investment incentives.

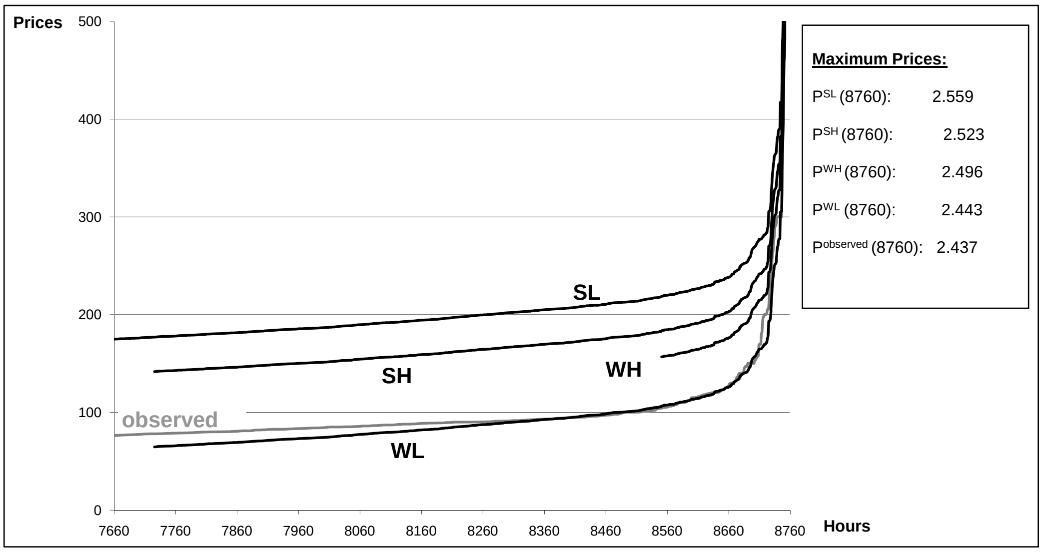


Figure 3: Price Distribution in the Hours where Capacity is Binding, Cases SH, SL, WH, WL, and Observed Prices.

From the predicted capacity levels we now compute the price distribution for those hours where capacity is predicted to be binding in the Cournot game. Since we want to compare predicted prices to the observed price distribution, we choose (in accordance with the German market structure) a scenario of four firms. We, moreover, choose the mean

[32]The German market consists essentially of four large players. Two of them (RWE and E.on) have a market share of 26 % each, while the two smaller ones (ENBW and Vattenfall) together cover 30 % of the market each. Compare, e.g., Monopolkommission (2007).

values of the parameter intervals which we used in our simulations, i.e. $b = 0.0055$, and $k = 35430/MWa$.[33] For our data set strategic firms are capacity constrained in approximately 1107 hours (12.6 % of the year).[34] Figure 3 provides the observed price distribution (grey line), as well as the predicted price distributions during the hours with a binding capacity constraint, separately for scenarios WL, WH, SH, and SL (black lines). In order to make the differences more visible, in the figure we focus on prices in the interval $[0, 500]$ and provide information on the highest price realizations in the legend. Obviously, for the parameter configuration we chose, observed prices are above predicted prices in the first best scenario but well below predicted prices in the Cournot market game. All depicted prices reflect the willingness to pay for an additional unit of capacity that cannot be produced in the short run. Notice that the relatively low level of observed prices (as compared to the Cournot scenario) may well be due to the fact that currently firms have more capacity installed than they would have chosen in a liberalized regime.[35] Strategic investment would strongly affect the price distribution, as comparison of the curves for the cases $WL$ and $SH$ illustrates. Obviously, there is a strong potential for market power not only in the short run, but also at the investment stage.

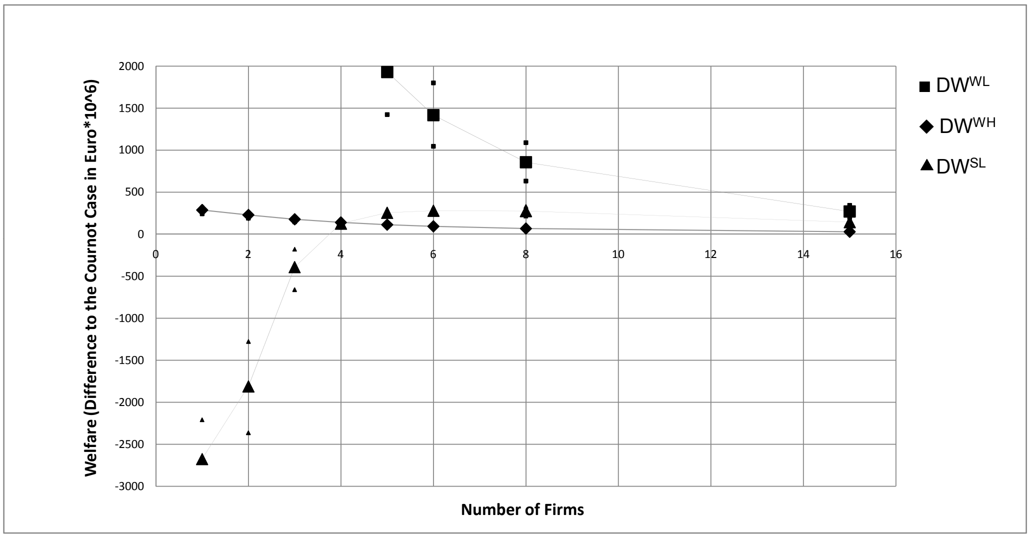


Figure 4: Welfare Differences relative to Case SH for Cases $SL$, $WH$, and $WL$.

[33] We could also determine the price distribution for ranges of parameters. Since capacities have turned out not to be very sensitive to changes in the parameters, however, we chose to use mean values to make our illustration more readable.

[34] Our predicted values match the empirical observations. Due to Umweltbundesamt (2004), gas turbines run approximately 10 % of the time.

[35] In the pre-liberalization period, generators where subject to a rate of return regulation that imposed excessive investment incentives.

Finally, figure 4 illustrates the welfare effect that results from more competitive spot market behavior (e. g. enforced by the regulatory authorities). All welfare differences are calculated in relation to the strategic investment game with high spot market prices. Again, we ran simulations using the relevant parameter ranges. Big symbols represent average welfare differences while small symbols are the 90 % confidence intervals. As we have already seen from the theoretical analysis and from figure 2, imposing marginal cost prices at the spot market considerably decreases equilibrium investment. The figure shows that if the number of firms in the market is low, competitive spot market behavior significantly decreases total welfare (as compared to Cournot spot markets). Only if the number of firms is four or higher, total welfare is increasing. Thus, our analysis demonstrates that regulatory intervention only at the spot market does not necessarily have the desired effect if firms choose their capacities strategically.

The figure moreover illustrates the welfare effect of intervention only at the investment stage (scenario WH) and of implementation of the welfare optimum. As it becomes clear from the graph, performance of the Cournot market game is getting very close to the welfare optimum as the number of competitors becomes large. We also observe that, while the effect of increasing capacities given that firms have market power at the spot market is moderate for all market structures, intervention at the spot market may have relatively large negative effects on welfare if the number of firms is low.

# 5 Conclusion

In this paper we have provided a model of strategic investment prior to a series of spot markets with fluctuating and potentially uncertain demand. Explicit modeling of demand fluctuations is central when the good under consideration is not storable. In this case, when making their investment decisions, firms have to take into account that capacity will remain unused in low demand scenarios while they will produce at the capacity bound in high demand scenarios. The main focus of our paper was (i) to analyze the impact of spot market design on investment incentives of strategic firms and (ii) to study how the consideration of strategic firms affects conclusions on the desirability of alternative spot market rules (as compared to the traditional peak–load pricing approach, where welfare is maximized).

The main motivation for our paper was to model investment in electricity markets. We thus built on earlier research on electricity spot market competition and extended the analysis by an investment stage. One of the most common approaches to model electricity spot markets is the concept of supply function competition by Klemperer and Meyer (1989) which has been applied to the case of electricity markets by Green and Newbery (1992).

The supply function game typically has multiple equilibria which range from the competitive market outcome (lower bound) to the Cournot solution (upper bound).[36] Which of the equilibria is being played in a particular market likely depends on specific market rules and institutions. In a dynamic investment game a continuum of equilibria at the production stage implies very imprecise overall equilibrium predictions ranging up to the collusive outcome (folk theorems). In order to obtain meaingful solutions for the strategic investment game we thus limited our analysis to the two extreme cases, the Cournot and the competitive solution. This allowed us to pin down the effect of expected spot market prices on investment incentives of strategic firms. Alternatively, one could use a specification of the supply function model that yields a unique equilibrium prediction, as for example provided by Holmberg (2008).

Let us briefly summarize our main results. We have shown that if firms invest strategically the common intuition that spot markets should be more competitive is misleading. The reason is that more competitive spot markets imply lower investment incentives, which leads to higher scarcity prices, possibly also implies higher average prices and a welfare reduction. Our results also hold under free entry of firms. Those findings are in contrast to a well known result of the peak–load–pricing literature. This literature, which has analyzed optimal investment in a similar environment, comes to the conclusion that optimal investment (of non-strategic firms) is the higher, the more competitive the spot market is. Our findings demonstrate that it is not possible to "approximate" strategic investment behavior by just using the results from the peak load pricing literature, which is often done in applied electricity market research.[37] We thus show that investment incentives and spot design cannot be considered as two separate problems but are closely interconnected. In order to properly assess the quality of spot market design it is indispensable to account for the interaction of investment incentives and spot market behavior — and to model strategic players explicitly.

In order to quantify the effects we identified in the theoretical part of the paper we fitted our model to data of the German electricity market. We derived predicted investment levels for various degrees of market concentration, and illustrated welfare effects of changing from a Cournot spot market to a competitive spot market outcome. In a market of four firms (which corresponds to the current situation in Germany) predicted strategic capacity choices are at 80 % of the capacity unstrategic firms would choose prior to a competitive spot market[38], while installed capacity is even at approximately 96 % of this "competitive benchmark". This is presumably due to high investment incentives in the

[36]Especially when uncertainty regarding demand at each single spot market is small, the Cournot and the competitive solution are indeed the lowest and the highest equilibrium.

[37]See, for example, Boccard (2009), Bushnell (2005), Cramton and Stoft (2005), or Joskow (2007).

[38]This solution is also welfare maximizing.

pre–liberalization period. In accordance with the relatively high current capacity level, the observed distribution of prices in 2006 is close to the predicted "competitive benchmark" price distribution for those scenarios where our model predicts that capacity is binding. Moreover, for a market structure of four firms we find a slightly positive welfare effect of changing from a Cournot spot market to competitive spot market prices. For highly concentrated markets (i.e. monopoly or duopoly), strategic capacity choices are far below the level that unstrategic firms would choose. We thus find that in concentrated markets, changing from Cournot–prices to competitive prices at the spot market would decrease the investment incentives drastically and would therefore have a large and negative welfare effect.

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# A Analysis of the Production Stage

The appendix contains all proofs of the paper. In the first part (appendices A.1 and A.2), we analyze spot market behavior, which we need in order to prove theorems 1 (appendix B) and 2 (appendix C).

In the first step we characterize capacity constrained production choices at the spot market for each $\theta$ given investment choices $x$. Note that we have to consider also asymmetric investment scenarios. In order to simplify the exposition we will order the firms according to their investment levels, i. e. $x_1 \leq x_2 \leq \cdots \leq x_n$, throughout the paper. At the spot market either firms engage in Cournot competition or the behave competitively (i. e. because a social planer implements the optimal production schedule given investment choices or because firms choose a low supply function equilibrium). In the following two subsections we analyze both scenarios.

## A.1 Properties of the Highest Spot Market Outcome (Capacity Constrained Cournot Game)

An equilibrium of the capacity constrained Cournot game at the spot market in scenario $\theta$ given $x$, $q^H(x, \theta)$, satisfies simultaneously for all firms

$$q_i^H(x, \theta) \in \arg\max_{\mathrm{q}} \left\{ P(\mathrm{q} + q_{-i}^H, \theta))\mathrm{q} - C(\mathrm{q}, \theta) \right\} \qquad \text{s.t.} \quad 0 \leq \mathrm{q} \leq x_i. \tag{3}$$

Note that at very low values of $\theta$ all firms are necessarily unconstrained. By assumption 1 the unconstrained Cournot equilibrium [which we denote by $\tilde{q}^{H0}(\theta)$] is unique and symmetric for each $\theta \in [-\infty, \infty]$.[39] From (3) it follows that $\tilde{q}_i^{H0}(\theta)$ is implicitly determined by the first order condition

$$P(n\tilde{q}_i^{H0}, \theta) + P_q(n\tilde{q}_i^{H0}, \theta)\tilde{q}_i^{H0} = C_q(\tilde{q}_i^{H0}, \theta).$$

[39]See, for example Selten (1970), or Vives (2001), pp. 97/98.

Now as $\theta$ increases, at some critical value that we denote by $\theta^{H1}(x)$, firm 1 (the one with the lowest capacity) becomes constrained. The critical demand scenario is implicitly determined by $x_1 = q_1^{H0}(\theta^{H1})$. If it holds that $x_1 < x_2$, then at $\theta^{H1}(x)$ only firm one becomes constrained. Then, in equilibrium, firm 1 produces at its capacity bound whereas the remaining firms produce their equilibrium output of the Cournot game among $n-1$ firms given the residual demand $P(Q - x_1, \theta)$ [denoted by $\tilde{q}_i^{H1}(x, \theta)$], which solves the first order condition

$$P(x_1 + (n-1)\tilde{q}_i^{H1}, \theta) + P_q(x_1 + (n-1)\tilde{q}_i^{H1}, \theta)\tilde{q}_i^{H1} = C_q(\tilde{q}_i^{H1}, \theta).$$

The capacity constrained Cournot equilibrium in the case where one firm is constrained is a vector $q^{H1}(x, \theta)$, where $q_i^{H1}(x, \theta) = \min\{x_i, \tilde{q}^{H1}(x, \theta)\}$.

As $\theta$ increases further, we pass through $n+1$ cases, from case $H0$ (no firm is constrained) to case $Hn$ (all $n$ firms are constrained). Note that two critical values $\theta^{Hm}(x)$ and $\theta^{Hm+1}(x)$ coincide whenever $x_m = x_{m+1}$, and that it holds that $\theta^{Hm}(x) < \theta^{Hm+1}(x)$ (by assumption 2) whenever $x_m < x_{m+1}$.

Now we are prepared to characterize the capacity constrained Cournot equilibrium in case $Hm$ where $m$ firms are constrained. In this case, the $m$ firms with the lowest capacities produce at their capacity bound, whereas the $n-m$ unconstrained firms produce

$$\begin{aligned} \tilde{q}_i^{Hm}(x, \theta) \quad = \quad & \left\{ q_i \in \mathbb{R} : P\left(\sum_{i=1}^{m} x_i + (n-m)\,\tilde{q}_i^{Hm}, \theta\right) \right. \\ & \left. + P_q\left(\sum_{i=1}^{m} x_i + (n-m)\,\tilde{q}_i^{Hm}, \theta\right)\tilde{q}_i^{Hm} = C_q\left(\tilde{q}_i^{Hm}, \theta\right) \right\}, \end{aligned} \tag{4}$$

The equilibrium quantities of the capacity constrained Cournot game in case $Hm$ are given by

$$q_i^{Hm}(x, \theta) = \min\{x_i, \tilde{q}_i^{Hm}(x, \theta)\}, \tag{5}$$

and aggregate production in case $Hm$ is

$$Q^{Hm}(x, \theta) = \sum_{i=1}^{n} q_i^{Hm}(x, \theta). \tag{6}$$

This allows us finally to pin down the profit of firm $i$ in scenario $Hm$,

$$\pi_i^{Hm}(x, \theta) = \begin{cases} P\left(Q^{Hm}, \theta\right) x_i - C\left(x_i, \theta\right) & \text{if } i \leq m, \\ \\ P\left(Q^{Hm}, \theta\right) \tilde{q}_i^{Hm}(x, \theta) - C\left(\tilde{q}_i^{Hm}(x, \theta), \theta\right) & \text{if } i > m. \end{cases} \tag{7}$$

Note that it holds that $\frac{d\pi_i^{Hm}}{dx_i} > 0$ only if $i \leq m$, and $\frac{d\pi_i^{Hm}}{dx_i} = 0$ otherwise, since a firm's capacity expansion only affects production at the spot market in case the firm was constrained. Obviously, in this case the derivative must be positive.

We can finally pin down maximal social welfare generated in demand scenario $\theta \in [\theta^{Hm}, \theta^{Hm+1}]$ (where, given $x$, the $m$ lowest capacity firms are constrained) as

$$W^{Hm}(x,\theta) = \int_0^{Q^{Hm}(x,\theta)} P(Q,\theta)\, dQ - \sum_{i=1}^{n} C\left(q_i^{Hm}(x,\theta), \theta\right). \tag{8}$$

(we need this in order to prove Part (WH) of theorem 2). Note that $W^{Lm}$ only depends on $x_i$ if firm $i$ is constrained in scenario $m$, that is if $i \leq m$.

Lemma 1 (Monotonicity of $\theta^{Hm}$) *$\frac{d\theta^{Hm}(x)}{dx_i}$ is strictly positive if $i \leq m$ (i.e. if firm $i$ produces at its capacity bound), and zero otherwise.*

Proof $\theta^{Hm}(x)$ is the demand realization from which on firm $m$ cannot play its unconstrained output any more. At $\theta^{Hm}(x)$ it holds that $q_i^H(\theta^{Hm}(x)) = \tilde{q}_i^{Hm}(\theta^{Hm}(x)) = x_m$ for all $i \geq m$ and $q_i^H(\theta^{Hm}(x)) = x_i < x_m$ for all $i < m$. Thus, $\theta^{Hm}(x)$ is implicitly defined by the conditions

$$\begin{aligned} & P\left(\sum_{i=1}^{m} x_i + (n-m)x_m, \theta^{Hm}(x)\right) \\ & \quad + P_q\left(\sum_{i=1}^{m} x_i + (n-m)x_m, \theta^{Hm}(x)\right) x_m - C_q\left(x_m, \theta^{Hm}(x)\right) = 0. \end{aligned}$$

Differentiation with respect to $x_i$, $i < m$, yields

$$P_q(\cdot) + P_\theta(\cdot)\frac{d\theta^{Hm}(x)}{dx_i} + P_{qq}(\cdot)\, x_m + P_{q\theta}(\cdot)\, x_m \frac{d\theta^{Hm}(x)}{dx_i} - C_{q\theta}(\cdot)\frac{d\theta^{Hm}(x)}{dx_i} = 0,$$

and solving for $\frac{d\theta^{Hm}(x)}{dx_i}$ we obtain

$$\frac{d\theta^{Hm}(x)}{dx_i} = -\frac{P_q(\cdot) + P_{qq}(\cdot)\, x_m}{P_\theta(\cdot) + P_{q\theta}(\cdot)\, x_m - C_{q\theta}(\cdot)} > 0$$

due to assumption 1, part (i) and assumption 2, part (ii) [note that the expression in the denominator is the cross derivative which was assumed to be positive in part (ii) of assumption 2].

Differentiation with respect to $x_i$, $i = m$, yields

$$\begin{aligned} & (n-m+2)P_q(\cdot) + P_\theta(\cdot)\frac{d\theta^{Hm}(x)}{dx_i} \\ & \quad + (n-m+1)P_{qq}(\cdot)\, x_m + P_{x\theta}(\cdot)\, x_m \frac{d\theta^{Hm}(x)}{dx_i} - C_{xx}(\cdot) - C_{q\theta}(\cdot)\frac{d\theta^{Hm}(x)}{dx_i} = 0, \end{aligned}$$

and solving for $\frac{d\theta^{Hm}(x)}{dx_i}$ we obtain

$$\frac{d\theta^{Hm}(x)}{dx_i} = -\frac{(n-m+2)P_q(\cdot) + (n-m+1)P_{qq}(\cdot)\, x_m - C_{xx}(\cdot)}{P_\theta(\cdot) + P_{q\theta}(\cdot)\, x_m - C_{q\theta}(\cdot)} > 0,$$

also due to assumption 1, parts (i) and assumption 2, part (ii). Finally, differentiation with respect to $x_i$, $i > m$, yields

$$P_\theta (\cdot) \frac{d\theta^{Hm}(x)}{dx_i} + P_{x\theta}(\cdot) x_m \frac{d\theta^{Hm}(x)}{dx_i} - C_{q\theta}(\cdot) \frac{d\theta^{Hm}(x)}{dx_i} = 0,$$

which implies that $\frac{d\theta^{Hm}(x)}{dx_i} = 0$ for $i > m$. □

## A.2 Properties of the Lowest Spot Market Outcome (Competitive Behavior)

In the following we specify, for a given vector of capacities $x$, the competitive (welfare optimal) production schedule for any possible demand scenario (that is, for any possible value of $\theta$).

Note that necessarily all firms are unconstrained for very low values of $\theta$. It is straightforward to show that in the welfare optimum, all unconstrained firms produce the same (due to convex cost). Thus, the socially optimal total quantity of each firm if all firms are unconstrained is given by $q_i^{L0}(\theta) = \{q_i \in \mathbb{R} : P(nq_i, \theta) = C_q(q_i, \theta)\}$.

Now, as $\theta$ increases, at some critical value, that we denote by $\theta^{L1}(x)$, firm 1 (the lowest capacity firm) becomes constrained. The critical demand scenario $\theta^{L1}(x)$ is implicitly defined by $x_1 = q_1^{L0}(\theta^{L1})$. If it holds that $x_1 < x_2$, then at $\theta^{L1}(x)$ only firm 1 becomes constrained and the socially optimal (competitive) production plan implies that firm 1 produces at its capacity bound whereas the remaining firms produce the unconstrained optimal quantity given the residual demand $P(Q - x_1, \theta)$, i. e. $\tilde{q}_i^{L1}(x, \theta) = \{q_i \in \mathbb{R} : P((n-1)q_i + x_1, \theta) = C_q(q_i, \theta)\}$. The optimal production plan in scenario $L1$ is a vector $q^{L1}(x, \theta)$, where each element is given by $q_i^{L1}(x, \theta) = \min\{x_i, \tilde{q}_i^{L1}(x, \theta)\}$.

As $\theta$ increases further and more firms become constrained, we pass through $n+1$ cases, from case $L0$ (no firm is constrained) to case $Ln$ (all $n$ firms are constrained). Note that two critical values $\theta^{Lm}(x)$ and $\theta^{Lm+1}(x)$ coincide whenever $x_m = x_{m+1}$, and that it holds that $\theta^{Lm}(x) < \theta^{Lm+1}(x)$ (by assumption 2) whenever $x_m < x_{m+1}$.

Now we are prepared to characterize the socially optimal production plan and social welfare generated in case $Lm$, where $m$ firms are constrained. In this case, the $m$ firms with the lowest capacities produce at their capacity bound, whereas the $n-m$ unconstrained firms produce the unconstrained optimal quantity given the residual demand $P(Q - \sum_{i=1}^m x_i, \theta)$, i. e.

$$\tilde{q}_i^{Lm}(x, \theta) = \left\{ q_i \in \mathbb{R} : P\left( \sum_{j=1}^m x_j + (n-m)q_i, \theta \right) = C_q(q_i, \theta) \right\}. \tag{9}$$

We denote the optimal production plan in case $Lm$ by $q^{Lm}(x, \theta)$ where each element is given by

$$q_i^{Lm}(x,\theta) = \min\{x_i, \tilde{q}_i^{Lm}(x,\theta)\} \qquad i = 1,\ldots,n. \tag{10}$$

Consequently, the optimal total quantity produced in case $Lm$ is

$$Q^{Lm}(x,\theta) = \sum_{i=1}^{n} q_i^{Lm}(x,\theta). \tag{11}$$

This allows to pin down firm $i$'s profit in scenario $Lm$,

$$\pi_i^{Lm}(x,\theta) = \begin{cases} P\left(Q^{Lm}(x,\theta),\theta\right) x_i - C\left(x_i,\theta\right) & \text{if} \quad i \le m, \\ \\ P\left(Q^{Lm}(x,\theta),\theta\right) \tilde{q}_i^{Lm}(x,\theta) - C\left(\tilde{q}_i^{Lm}(\cdot),\theta\right) & \text{if} \quad i > m. \end{cases} \tag{12}$$

We can finally pin down maximal social welfare generated in demand scenario $\theta \in [\theta^{Lm}, \theta^{Lm+1}]$ (where, given $x$, the $m$ lowest capacity firms are constrained) as

$$W^{Lm}(x,\theta) = \int_0^{Q^{Lm}(x,\theta)} P(Q,\theta)\, dQ - \sum_{i=1}^{n} C\left(q_i^{Lm}(x,\theta),\theta\right). \tag{13}$$

(we need this in the proof of theorem 2). Note that $W^{Lm}$ only depends on $x_i$ if firm $i$ is constrained in scenario $m$, that is if $i \le m$.

# B Proof of Theorem 1

## B.1 Proof of Theorem 1, Case (SH, Strategic Firms — High Spot Market Prices)

Now we are prepared to analyze capacity choices at the investment stage. The results obtained for spot market behavior enable us to derive a firm $i$'s profit from investing $x_i$, given that the other firms invest $x_{-i}$ and quantity choices at the spot markets are given by $q^{Hm}(x,\theta)$ for $\theta \in [\theta^{Hm}(x), \theta^{Hm+1}(x)]$. Recall that when choosing capacities the firms anticipate demand fluctuations. Thus, a firm's profit from given levels of investments, $x$, is the integral over equilibrium profits at each $\theta$ given $x$ on the domain $[-\infty,\infty]$, taking into account the distribution over the demand scenarios. For each $\theta$, firms anticipate equilibrium play at the spot markets, which gives rise to one of the $n+1$ types of equilibria, $EQ^{H0}$, ..., $EQ^{Hm}$, ..., $EQ^{Hn}$. Note that any $x > 0$ gives rise to the unconstrained equilibrium if $\theta$ is sufficiently low. As $\theta$ increases, more and more firms become constrained. Thus, a tuple of investment levels that initially gave rise to an $EQ^{H0}$, then leads to an equilibrium where first one (then two, three, ..., and finally $n$) firms are constrained. In order to simplify the exposition we define $\theta^{H0} \equiv -\infty$ and $\theta^{Hn+1} \equiv \infty$. Then, the profit of firm $i$ is given by[40]

$$\pi_i(x, q^H) = \sum_{m=0}^{m=n} \int_{\theta^{Hm}}^{\theta^{Hm+1}} \pi_i^{Hm}(x,\theta) dF(\theta) - K(x_i). \tag{14}$$

Note that at each critical value $\theta^{Hm}$, $m = 1, \dots, n$ it holds that $\pi^{Hm-1}(x, \theta^{Hm}) = \pi^{Hm}(x, \theta^{Hm})$. Thus, $\pi_i(x, q^H)$ is continuous. Differentiating $\pi_i(x, q^H)$ yields[41]

$$\frac{d\pi_i\left(x, q^H\right)}{dx_i} = \sum_{m=i}^{n} \int_{\theta^{Hm}(x)}^{\theta^{Hm+1}(x)} \frac{d\pi_i^{Hm}(x,\theta)}{dx_i} dF(\theta) - K_x(x_i) \tag{15}$$

We prove part (i) of the lemma in two steps. In part I we show existence and in part II uniqueness of the equilibrium.

**Part I: Existence of Equilibrium** In the following we show that a symmetric equilibrium of the investment game exists if firms invest strategically and expect high spot market prices (case SH), and that equilibrium choices $x_i^{SH} = \frac{1}{n} X^{SH}$, $i = 1, \dots, n$, are implicitly defined by equation (2). For this purpose it is sufficient to show quasiconcavity of firm $i$'s profit given the other firms invest $x_{-i}^{SH}$, $\pi_i(x_i, x_{-i}^{SH})$, which we do in the following.

Note that $\pi_i(x_i, x_{-i}^{SH})$ is defined piecewisely. For $x_i < x_i^{SH}$, we have to examine the profit of firm 1 (by convention the lowest capacity firm) given that $x_2 = x_3 = \dots = x_n$. Since this implies that $\theta^{H2} = \dots = \theta^{Hn}$ and thus it follows from (14) that

$$\begin{aligned} \pi_1(x_1, x_{-1}^{SH}) &= \int_{-\infty}^{\theta^{H1}(x)} \pi_1^{H0}(x,\theta) dF(\theta) + \int_{\theta^{H1}(x)}^{\theta^{Hn}(x)} \pi_1^{H1}(x,\theta) dF(\theta) \\ &\quad + \int_{\theta^{Hn}(x)}^{\infty} \pi_i^{Hn}(x,\theta) dF(\theta) - K(x_1) \end{aligned} \tag{16}$$

For $x_i > x_i^{SH}$, the profit of firm $i$ is the profit of the highest capacity firm (firm $n$ according to our convention), given all other firm have invested the same, i. e. $x_1 = \dots = x_{n-1}$. We get

$$\begin{aligned} \pi_n(x_n, x_{-n}^{SH}) &= \int_{-\infty}^{\theta^{Hn-1}(x)} \pi_n^{H0}(x,\theta) dF(\theta) + \int_{\theta^{Hn-1}(x)}^{\theta^{Hn}(x)} \pi_n^{Hn-1}(x,\theta) dF(\theta) \\ &\quad + \int_{\theta^{Hn}(x)}^{\infty} \pi_n^{Hn}(x,\theta) dF(\theta) - K(x_1) \end{aligned} \tag{17}$$

[40] Note that it is never optimal for a firm to be unconstrained at $\infty$ and thus, we always obtain $\theta^{Hn} \leq \infty$.

[41] Note that continuity of $\pi_i$ implies that due to Leibnitz' rule the derivatives of the integration limits cancel out. Moreover, $\pi_i^{Hm}$ only changes in $x_i$ if firm $i$ is constrained in scenario $Lm$, i. e. $i \leq m$. Thus, the sum does not include the cases where firm $i$ is unconstrained, i. e. $m < i$.

**(i) The shape of $\pi_i(x_i, x_{-i}^{SH})$ for $x_i > x_i^{SH}$:** The second derivative of the profit function $\pi_n$ is given by[42]

$$\frac{d^2\pi_n}{(dx_n)^2} = -\frac{d\theta^{Hn}(x)}{dx_n} \underbrace{\left[\frac{d\pi_n^{Hn}(x,\theta^{Hn})}{dx_n}\right]}_{=0\ (x_n \text{ is opt. at} \theta^{Hn})} f(\theta^{Hn}) + \int_{\theta^{Hn}(x)}^{\infty} \underbrace{\frac{d^2\pi_n^{Hn}(x,\theta)}{(dx_n)^2}}_{<0 \text{ by A1 part (iv)}} f(\theta)d\theta < 0. \tag{18}$$

Note that the first term cancels out and the second term is negative by concavity of the spot market profit function (implied by assumption 1). We find that for $x_i \geq x_i^{SH}$, $\pi_i(x_i, x_{-i}^{SH})$ is concave, which implies that upwards deviations are not profitable.

**(ii) The shape of $\pi_i(x_i, x_{-i}^{SH})$ for $x_i < x_i^{SH}$:** This region is more difficult to analyze since the profit function $\pi_1(x_1, x_{-1}^{SH})$ is not concave. We can, however, show quasiconcavity of $\pi_1(x_1, x_{-1}^{SH})$. For this purpose we need lemma 2 (below) in order to complete the proof of existence (part I). We can show quasiconcavity of $\pi_1(x_1, x_{-1}^{SH})$ by showing that

$$\frac{d\pi_1(x_1^0, x_{-1}^{SH})}{dx_1} > \frac{d\pi_1(x_1^{SH}, x_{-1}^{SH})}{dx_1} = 0 \qquad \text{for all} \quad x_1^0 < x_1^{SH}.$$

This holds true, since [compare also equation (15)]

$$\begin{aligned}
\frac{d\pi_1(x_1^0, x_{-1}^{SH})}{dx_1} &= \underbrace{\int_{\theta^{H1}(x_1^0, x_{-1}^{SH})}^{\theta^{Hn}(x_1^0, x_{-1}^{SH})} \frac{d\pi_1^{H1}(x_1^0, x_{-1}^{SH}, \theta)}{dx_1} dF(\theta)}_{\geq 0 \quad \text{by lemma 2, part (i)}} + \int_{\theta^{Hn}(x_1^0, x_{-1}^{SH})}^{\infty} \frac{d\pi_1^{Hn}(x_1^0, x_{-1}^{SH}, \theta)}{dx_1} dF(\theta) \\
&\geq \int_{\theta^{Hn}(x_1^0, x_{-1}^{SH})}^{\infty} \frac{d\pi_1^{Hn}(x_1^0, x_{-1}^{SH}, \theta)}{dx_1} dF(\theta) \\
&= \underbrace{\int_{\theta^{Hn}(x_1^0, x_{-1}^{SH})}^{\theta^{Hn}(x_{-1}^{SH}, x_{-1}^{SH})} \frac{d\pi_1^{Hn}(x_1^0, x_{-1}^{SH}, \theta)}{dx_1} dF(\theta)}_{\geq 0 \quad \text{by properties 1 and 2, part (ii)}} \\
&\quad + \underbrace{\int_{\theta^{Hn}(x_1^{SH}, x_{-1}^{SH})}^{\infty} \left[\frac{d\pi_1^{Hn}(x_1^0, x_{-1}^{SH}, \theta)}{dx_1} - \frac{d\pi_1^{Hn}(x_1^{SH}, x_{-1}^{SH}, \theta)}{dx_1}\right] dF(\theta)}_{>0 \quad \text{by lemma 2, part (ii)}} \\
&\quad + \underbrace{\int_{\theta^{Hn}(x_1^{SH}, x_{-1}^{SH})}^{\infty} \frac{d\pi_1^{Hn}(x_1^{SH}, x_{-1}^{SH}, \theta)}{dx_1} dF(\theta)}_{= \frac{d\pi_i(x^{SH})}{dx_i} = 0 \text{ [recall that } \theta^{H1}(x^{SH}) = \theta^{Hn}(x^{SH})]} \geq 0.
\end{aligned}$$

To summarize, in part I (i) and (ii) we have shown that $\pi_i(x_i, x_i^{SH})$ is quasiconcave. We conclude that the first order condition given in theorem 1 indeed characterizes equilibrium capacities in the investment game with Cournot–style spot market competition.

[42] It is obvious that there is no incentive for any firm to deviate such that it is unconstrained at $\infty$. Thus, we only consider the case that all firms are constrained at $\infty$.

Lemma 2 [Properties of Marginal Profits at Stage Two] *Suppose all firms but firm 1 have invested symmetric capacities summarized in the vector $x^0_{-1}$. Firm* 1 *has invested* $x_1$*, less than each of the other firms. We obtain:*

*(i)* $\frac{d\pi_1^{H1}(x_1^0, x_{-1}^0, \theta)}{dx_1} \geq 0$ *for* $\theta^{H1} \leq \theta \leq \theta^{Hn}$.

*(ii)* $\frac{d\pi_1^{Hn}(x_1', x_{-1}^0, \theta)}{dx_1} \geq \frac{d\pi_1^{Hn}(x_1'', x_{-1}^0, \theta)}{dx_1} \geq 0 \quad$ *for* $\quad x_1' < x_1''$, $\theta^{Hn} \leq \theta \leq \infty$.

Proof (i) The first part holds due to the fact in case firm 1 is constrained, i. e. ($\theta \geq \theta^{H1}$), firm 1 would like to produce more than $x_1$ for all demand realizations $\theta \geq \theta^{H1}$, which, however, is not possible due to the capacity constraint.
(ii) The first inequality follows from concavity of the profit functions in the spot markets, which is implied by assumption 1. Thus, the first order condition at each spot-market is decreasing in $x_1$ until $\tilde{q}_i^{H0}$, which immediately yields the first inequality of part (ii). The second inequality is due to the fact that in case all firms are constrained, i. e. ($\theta \in [\theta^{Hn}, \infty]$), firm 1 would like to produce more for all demand realizations $\theta$ (which is not possible because it is constrained). □

**Part II: Uniqueness** In this part we show that (i) $x^{SH}$ is the unique symmetric equilibrium and (ii) that there are no asymmetric equilibria.

**(i) $x^{SH}$ is the unique symmetric equilibrium.** If capacities are equal, i. e. $x_1^0 = x_2^0 = \cdots = x_n^0$, we have

$$\frac{d\pi_i(x^0)}{dx_i} = \int_{\theta^{Hn}(x^0)}^{\infty} [P(nx_i^0, \theta) + P_q(nx_i^0, \theta)x_i^0 - C_q(x_i^0, \theta)]f(\theta)d\theta - K_x(x_i^0).$$

Differentiation yields[43]

$$\frac{d^2\pi_i(x^0)}{(dx_i)^2} = \int_{\theta^{Hn}(x^0)}^{\infty} \left[(n+1)P_q(nx_i^0, \theta) + nP_{qq}(nx_i^0, \theta)x_i^0 - C_{qq}(x_i^0, \theta)\right] dF(\theta) - K_{xx}(x_i^0) < 0,$$

which is negative due to assumption 1. Thus, since $\frac{d\pi_i(x^{SH})}{dx_i} = 0$ and moreover $\pi_i(x)$ is concave along the symmetry line, no other symmetric equilibrium can exist.

**(ii) There cannot exist an asymmetric equilibrium.** Any candidate for an asymmetric equilibrium $\hat{x}$ can be ordered such that $\hat{x}_1 \leq \hat{x}_2 \leq \cdots \leq \hat{x}_n$, where at least one inequality has to hold strictly. This implies $\hat{x}_1 < \hat{x}_n$. The profit of firm $n$ can be obtained by setting $i = n$ in equation (14), and the first derivative is given by

$$\frac{d\pi_n}{dx_n} = \int_{\theta^{Hn}(x)}^{\infty} \frac{d\pi_n^{Hn}(x, \theta)}{dx_n} f(\theta)d\theta - K_x(x_n).$$

[43] Differentiation works as in (18).

It is easy to show that firm $n$'s profit function is concave by examination of the second derivative [see equation (18)]. Thus, any asymmetric equilibrium $\hat{x}$, if it exists, must satisfy $\frac{d\pi_n(\hat{x})}{dx_n} = 0$. We now show that whenever it holds that $\frac{d\pi_n(\hat{x})}{dx_n} = 0$, firm 1's profit is increasing in $x_1$ at $\hat{x}$ (which implies that no asymmetric equilibria exist).

From equation (15) it follows that the first derivative of firm 1's profit function is given by

$$\frac{d\pi_1}{dx_1} = \int_{\theta^{H1}(x)}^{\theta^{H2}(x)} \frac{d\pi_1^{Hn}(x,\theta)}{dx_1} f(\theta)d\theta + \cdots + \int_{\theta^{Hn}(x)}^{\infty} \frac{d\pi_1^{Hn}(x,\theta)}{dx_1} f(\theta)d\theta - K_x(x_1).$$

Note that all the integrals in $\frac{d\pi_1}{dx_1}$ are positive since firm 1 is constrained at all demand realizations and therefore would want to increase its production. Thus, we have

$$\frac{d\pi_1}{dx_1} > \int_{\theta^{Hn}(x)}^{\infty} \frac{d\pi_1^{Hn}(x,\theta)}{dx_1} f(\theta)d\theta - K_x(x_1),$$

where the RHS are simply the last two terms of $\frac{d\pi_1}{dx_1}$. Note furthermore that $\hat{x}_1 < \hat{x}_n$ also implies that $K_x(\hat{x}_1) < K_x(\hat{x}_n)$ (due to assumption 3) and

$$\frac{d\pi_1(\hat{x})}{dx_1} = P(\hat{x},\theta) + P_q(\hat{x},\theta)\hat{x}_1 - C_q(\hat{x}_1,\theta) < P(\hat{x},\theta) + P_q(\hat{x},\theta)\hat{x}_n - C_q(\hat{x}_n,\theta) = \frac{d\pi_n(\hat{x})}{dx_n}$$

(due to assumption 1). Now we can conclude that

$$\frac{d\pi_1}{dx_1} > \int_{\theta^{Hn}(x)}^{\infty} \frac{d\pi_1^{Hn}(x,\theta)}{dx_1} f(\theta)d\theta - K_x(x_1) > \int_{\theta^{Hn}(x)}^{\infty} \frac{d\pi_n^{Hn}(x,\theta)}{dx_n} f(\theta)d\theta - K_x(x_n) = 0.$$

The last equality is due to the fact that this part is equivalent to the first order condition of firm $n$, which is satisfied at $\hat{x}$ by construction. To summarize, we have shown that $\frac{d\pi_1}{dx_1} > 0$, which implies that there exist no asymmetric equilibria, since at any equilibrium candidate, firm 1 has an incentive to increase its capacity.

## B.2 Proof of Theorem 1, Case (SL, Strategic Firms — Low Spot Market Prices)

If firms behave competitively at the spot markets, firm $i$'s spot market–profit in scenario $\theta$ is given by (12). The investment stage expected profit of firm $i$ is obtained by integrating over all profits associated with each demand realization,[44]

$$\pi_i(x, q^L) = \sum_{m=0}^{n} \int_{\theta^{Lm}(x)}^{\theta^{Lm+1}(x)} \pi_i^{Lm}(x,\theta)dF(\theta) - K(x_i). \tag{19}$$

Thus, the first order condition is

$$\frac{d\pi_i\left(x, q^L\right)}{dx_i} = \sum_{m=i}^{n} \int_{\theta^{Lm}(x)}^{\theta^{Lm+1}(x)} \frac{d\pi_i^{Lm}(x,\theta)}{dx_i} dF(\theta) - K_x(x_i). \tag{20}$$

[44] We define $\theta^{L0} = -\infty$ and $\theta^{Ln+1} = \infty$.

Now note that $\frac{d\pi_i}{dx_i} > 0$ at $X = 0$ (since investment is gainful), that $\frac{d\pi_i}{dx_i} < 0$ for some finite value of $X$, and that $\frac{d\pi_i}{dx_i}$ is continuous. Thus, a corner solution is not possible, and we have at least one point where (2) is satisfied and $\frac{d\pi_i}{dx_i}$ is decreasing. Note, however, that this does not assure existence. In fact, in the scenario considered here a firm's investment stage profit is not even quasiconcave, and it is not possible to reformulate the game as a supermodular game.

Now assume constant marginal production cost. Note that in the case of constant marginal production costs it is, independently of the capacity choices firms made at the investment stage, always true that either all firms are constrained at $p = C_q(\cdot, \theta)$, or none of them. Thus, it holds that $\theta^{L1}(x) = \cdots = \theta^{Ln}(x)$.

In order to prove part (SL) of theorem 1, we apply theorem 2.1 of Amir and Lambson (2000), p. 239. They show that the standard Cournot oligopoly game has at least one symmetric equilibrium and no asymmetric equilibria whenever demand $P(\cdot)$ is continuously differentiable and decreasing, cost $C(\cdot)$ is twice continuously differentiable and nondecreasing and, moreover, the cross partial derivative $\frac{d\pi(X,q)}{dX_{-i}dX} > 0$, where $X$ denotes total capacity and $X_{-i}$ capacity chosen by the firms other than $i$. In order to see that the results of Amir and Lambson apply to our setup, note that our game is equivalent to a game where firms choose output given the *expected demand and cost* function. Note that if the first best outcome occurs whenever capacity is sufficient, it follows that expected inverse demand is given by

$$EP(X) = \int_{-\infty}^{\theta^{Ln}(x)} P\left(Q^{L0}(\theta), \theta\right) dF(\theta) + \int_{\theta^{Ln}(x)}^{\infty} P(X, \theta)\, dF(\theta), \tag{21}$$

and expected cost is given by

$$EC(x_i) = \int_{-\infty}^{\theta^{Ln}(x)} C\left(q_i^{L0}, \theta\right) dF(\theta) + \int_{\theta^{Ln}(x)}^{\infty} C(x_i, \theta)\, dF(\theta) + K(x_i), \tag{22}$$

Note that $EP(X)$ is strictly decreasing in $X$ and $EC(x_i)$ is strictly increasing in $x_i$, but they do not satisfy assumption 1, part (i), which is why existence and uniqueness are not implied by standard (textbook) analysis.[45] However, Amir and Lambson's assumptions[46] are satisfied, since the cross partial derivative

$$\begin{aligned}\frac{d\pi^2(X, q^H)}{dX_{-i}dX} &= -\frac{d\theta^{Ln}(x)}{dX} \underbrace{\left[-P(X, \theta^{Ln}(x)) + C_q(X - X_{-i}, \theta^{Ln}(x))\right]}_{=0 \text{ at } \theta^{Ln}(x)} f(\theta^{Ln}(x)) \\ &\quad + \int_{\theta^{Ln}(X)}^{\infty} \underbrace{\left[-P_q(X, \theta) + C_{qq}(X - X_{-i}, \theta)\right]}_{>0} f(\theta) d\theta\end{aligned}$$

[45] In fact, the expected profit function is not even quasiconcave, as it is easily seen by inspecting its second derivative.

[46] The assumptions are: $P(\cdot)$ is continuously differentiable with $P_q(\cdot) < 0$, $C(\cdot)$ is twice continuously differentiable and nondecreasing, and $P_q(X) - C_{qq}(x_i) < 0$.

is positive. This guarantees that we have at least one symmetric equilibrium and no asymmetric equilibria in case of constant marginal cost.

# C Proof of Theorem 2

The proof of theorem 2 (where welfare maximizing capacities are chosen) is quite similar to the proof of theorem 1. We therefore give only a brief sketch, and refer to a working paper version of the paper (Grimm and Zoettl (2007)) for an extensive version of the proof.

In order to prove part (WL), we consider for each realization of $\theta$ the welfare maximum at the spot market for fixed capacity choices. Integration over all realizations of spot market demand then yields expected welfare, which is given by the following expression:

$$\mathcal{W}(x, q^L) = \sum_{m=0}^{n} \int_{\theta^{Lm}(x)}^{\theta^{Lm+1}(x)} W^{Lm}(x, \theta) dF(\theta) - \sum_{i=1}^{n} K(x_i). \tag{23}$$

Note that at each critical value $\theta^{Lm}$, $m = 1, \ldots, n$, it holds that $W^{Lm-1}(x, \theta^{Lm}) = W^{Lm}(x, \theta^{Lm})$. Thus, $\mathcal{W}(x)$ is continuous. Differentiating $\mathcal{W}(x)$ yields the following first order condition:

$$\frac{d\mathcal{W}(x, q^L)}{dx_i} = \sum_{m=i}^{n} \int_{\theta^{Lm}(x)}^{\theta^{Lm+1}(x)} \frac{dW^{Lm}(x, \theta)}{dx_i} dF(\theta) - K_x(x_i) = 0. \tag{24}$$

After verification of the second order conditions we can conclude that the above first order condition (24) yields a unique and symmetric first best solution as stated in theorem 2, part (WL).

In order to proof part (WH), we need to determine welfare generated at the spot market at each realization of $\theta$ for fixed capacity choices given Cournot competition. Expected welfare is then again determined by integrating over all realizations of spot market demand and evaluation of first and second order conditions yields a unique and symmetric solution stated in the theorem.

# D Proof of Theorem 3

In appendices B and C we have shown that all games analyzed throughout this article have only symmetric equilibria. In the remaining three proofs we therefore simplify our notation of the critical demand scenarios in case of high and low demand. In the following, the critical demand realization $\theta^{Dj}$, where $D = \{L, H\}$ and $j = 0, \ldots, n$ will be denoted by $\theta^D$ (since in a symmetric solution all firms are constrained from the very same demand realization on) and unconstrained industry output $Q^{Dj}$, where $D = \{L, H\}$ and $j = 0, \dots, n$ can be denoted by $Q^D$ for symmetric investment.

Now consider the first order conditions that implicitly define total capacities in the four scenarios considered, as given in theorems 1 and 2. Recall that (i) $P_q(X,\theta) < 0$, and note that (ii) $\theta^H(x) > \theta^L(x)$ for all $x$. Furthermore, (iii) at (below, above) the demand realization $\theta^H(x^{SH})$ we have that $P_q(X^{SH},\theta)\frac{X^{SH}}{n} + P(X^{SH},\theta) - C_q(\frac{1}{n}X^{SH},\theta) = 0$ ($< 0$, $> 0$). Thus, the lefthand–sides of the first order conditions can be ordered as follows:

$$\begin{aligned}
WL: &\quad \int_{\theta^L(x)}^{\infty} \left[P(X,\theta) - C_q\left(\frac{1}{n}X,\theta\right)\right] dF(\theta) \\
WH: &\quad \geq \int_{\theta^H(x)}^{\infty} \left[P(X,\theta) - C_q\left(\frac{1}{n}X,\theta\right)\right] dF(\theta) \\
SH: &\quad > \int_{\theta^H(x)}^{\infty} \left[P_q(X,\theta)\frac{1}{n}X + P(X,\theta) - C_q\left(\frac{1}{n}X,\theta\right)\right] dF(\theta) \\
SL: &\quad \geq \int_{\theta^L(x)}^{\infty} \left[P_q(X,\theta)\frac{1}{n}X + P(X,\theta) - C_q\left(\frac{1}{n}X,\theta\right)\right] dF(\theta)
\end{aligned} \tag{25}$$

Note that according to theorems 1 and 2, the total capacities are determined as the values of $X$ where the respective term equals $K_x\left(\frac{1}{n}X^Z\right)$, $Z \in \{WL, WH, SH, SL\}$. Recall that in all cases we get interior solutions and note that the above terms (except for the one that determines $X^{SL}$) are decreasing in $X$, while $K_x$ is increasing in $X$. This immediately implies $X^{WL} \geq X^{WH} > X^{SH}$.

In order to see why the ranking stated in the theorem also holds for case $SL$, note that the above term in scenario $SH$ is strictly decreasing in $X$, whereas in scenario $SL$ the left hand side (LHS) of the first order condition satisfies $LHS(0) > K_x(0)$ (since investment is gainful) and $LHS(X) < K_x(X)$ for $X$ high enough. Since $K_x(X)$ is increasing in $X$, this immediately implies that for any equilibrium investment $X^{SL}$ it holds that $X^{SH} \geq X^{SL}$.

# E Proof Theorem 4

**Part (i).** We first determine welfare generated in case $WL$, where firms behave competitively at the spot markets and investment choice $X^{WL}$ is made such as to maximize welfare. At all spot markets $\theta < \theta^L(X^{WL})$ firms produce unconstrained output at marginal cost, generating welfare given by $W^L(\theta)$. For all spot markets $\theta \geq \theta^L(X^{WL})$ firms produce at their capacity bounds given by $X^{WL}$, generating welfare $\tilde{W}^L(\theta, X)$.

$$W^L(\theta) = \int_0^{Q^L(\theta)} P(Y,\theta)Y - nC(Y/n,\theta)dY, \quad \text{and} \quad \tilde{W}^L(\theta,X) = \int_0^X P(Y,\theta)Y - nC(Y/n,\theta)dY$$

Total welfare $W^{WL}$ is thus given by:

$$W^{WL} = \int_{-\infty}^{\theta^L(X^{WL})} W^L(\theta)dF(\theta) + \int_{\theta^L(X^{WL})}^{\infty} \tilde{W}^L(\theta, X^{WL})dF(\theta) - nK(X^{WL}/n)$$

Notice that for given investment choice a perfectly competitive spot market yields the welfare optimal spot market outcome. Since investment is chosen such as to maximize welfare, this implies that case $WL$ leads to the overall first best market outcome.

We now derive welfare generated in case $WH$. Firms choose spot market output $Q^H(\theta)$ strategically. For $\theta < \theta^L(X^{WH})$ capacity is not binding, we denote generated welfare at those spot markets by $W^H(\theta)$. For $\theta \geq \theta^L(X^{WH})$ firms produce at their capacity bounds, we denote generated welfare by $\tilde{W}^H(\theta, X)$.

$$W^H(\theta) = \int_0^{Q^H(\theta)} P(Y,\theta)Y - nC(Y/n,\theta)dY, \quad \text{and} \quad \tilde{W}^H(\theta, X) = \int_0^X P(Y,\theta)Y - nC(Y/n,\theta)dY$$

Total welfare $W^{WH}$ is then given by:

$$W^{WH} = \int_{-\infty}^{\theta^H(X^{WH})} W^H(\theta)dF(\theta) + \int_{\theta^H(X^{WH})}^{\infty} \tilde{W}^H(\theta, X^{WH})dF(\theta) - nK(X^{WH}/n)$$

Notice that in case $WH$, spot market output for given investment is not chosen such as to maximize welfare, but as the equilibrium of strategically interacting firms. This directly implies that welfare in case $WH$ is strictly lower than in case $WL$.

**Part (ii).** We now compare welfare generated in the cases $SL$ and $SH$. In case $SL$ firms at all spot markets $\theta < \theta^L(X^{SL})$ produce unconstrained output at marginal cost, generating welfare $W^L(\theta)$. For all spot markets $\theta \geq \theta^L(X^{SL})$ firms produce at their capacity bounds, generating welfare $\tilde{W}^L(\theta, X)$. We obtain for total welfare in case $SL$

$$W^{SL} = \int_{-\infty}^{\theta^L(X^{SL})} W^L(\theta)dF(\theta) + \int_{\theta^L(X^{SL})}^{\infty} \tilde{W}^L(\theta, X^{SL})dF(\theta) - nK(X^{SL}/n). \tag{26}$$

In case $SH$, firms choose spot market output $Q^H(\theta)$ strategically. For $\theta < \theta^L(X^{SH})$ capacity is not binding and welfare $W^H(\theta)$ is generated at each spot market. For $\theta \geq \theta^L(X^{SH})$ firms produce at their capacity bounds, generating welfare $\tilde{W}^H(\theta, X)$. We obtain for total welfare in case $SH$

$$W^{SH} = \int_{-\infty}^{\theta^H(X^{SH})} W^H(\theta)dF(\theta) + \int_{\theta^H(X^{SH})}^{\infty} \tilde{W}^H(\theta, X^{SH})dF(\theta) - nK(X^{SH}/n). \tag{27}$$

For low spot market realizations $\theta < \theta^L(X^{SL})$ capacities are binding neither in case $SH$, nor in case $SL$. For those low demand realizations welfare generated at more competitive spot markets (i.e. case $SL$) is clearly higher than for strategic spot market outcomes (i.e. case $SH$). For high spot market realizations $\theta \geq \theta^L(X^{SH})$, capacities are binding in both cases $SH$ and $SL$. Welfare generated in case $SH$ is now strictly bigger, since investment strictly exceeds investment of case $SL$ (see theorem 3). Which of those two effect dominates, depends on the precise structure of the market and the pattern of demand fluctuation. As we find, especially when market concentration is high, however, the implementation of a competitive spot market leads to a reduction of overall welfare. Moreover, as illustrated in figure 4, especially in highly strategic environments the impact of erroneous market design is substantial, however.

**Part (iii).** For the case of strategic investment, desirability of the more competitive spot market outcome depends on the precise parameters of the market game, as we have established in part (ii) of the theorem. In part (iii) we now establish a weaker statement, which is always true, however. As we find, a market designer will always overestimate the beneficial impact of implementing the competitive spot market outcome if basing his analysis on a framework of optimal investment but not of investment in a market equilibrium. In order to proof the theorem, we have to show $\left(W^{WL} + W^{SH}\right) \geq \left(W^{WH} + W^{SL}\right)$. This can be verified by point wise inspection for all spot market realizations $\theta$.

For spot market $\theta < \theta^H(X^{SH})$ firms can produce the unconstrained strategic spot market output in the cases $SH$ and $WH$. For case $SH$ this is true by definition of $\theta^H(X^{SH})$ and for case $WH$ this is true since $X^{SH} \leq X^{WH}$, as established in the proof of theorem 3. welfare generated in the cases $SH$ and $WH$ is thus identical for all those spot market realizations. Likewise, since $X^{WL} > X^{SL}$, welfare generated in case $WL$ weakly exceeds welfare generated in case $SL$ for those spot market realizations.

For $\theta \geq \theta^H(X^{SH})$ firms produce at the investment boundary for both cases $SH$ and $SL$. For case $SH$ this is true by definition of $\theta^H(X^{SH})$ and for case $SL$ this is true since $X^{SL} \leq X^{SH}$, as established in the proof of theorem 3. As already established in part (ii), whenever firms are constrained at the spot market, welfare generated in case $SH$ clearly exceeds welfare generated in case $SL$. Moreover, case $WL$ always outperforms case $WH$ in terms of welfare, no matter if capacities are binding or not (compare part (i)).

# F Proof of Theorem 5

We now consider the case of a free entry equilibrium. Entry is costly and firms enter the market as long as profits are non–negative. We first show that weakly less firms enter the market in case $SL$ as compared to case $SH$ in a free entry equilibrium, i.e. $n^{SL} \leq n^{SH}$. Remember in case $SH$, for $\theta < \theta^H$, firms produce in an unconstrained spot market equilibrium, and are capacity constrained for all higher demand realizations[47]. In case $SL$ for $\theta < \theta^L$ firms produce unconstrained spot market output at marginal cost and produce

[47] The free entry analysis obviously anticipates the symmetric equilibrium, established in theorem 1 as the solution of the investment market game. In order to save on notation we omit equilibrium investment $X^{SH}$ and $X^{SL}$ in the argument of the critical spot market realizations $\theta^H(X^{SH})$ and $\theta^L(X^{SL})$ respectively.

at the capacity bound for all higher demand realizations. We derive firms' profits for both cases ($SL$ and $SH$).

$$\pi_i^{SH}(n) = \int_{-\infty}^{\theta^H} \pi_i^{H0}\left(Q^H,\theta\right) dF(\theta) + \int_{\theta^H}^{\theta^L} \pi_i^{Hn}\left(X^{SH},\theta\right) dF(\theta) + \int_{\theta^L}^{\infty} \pi_i^{Hn}\left(X^{SH},\theta\right) dF(\theta) - K\left(X^{SH}/n\right) \quad (28)$$

$$\pi_i^{SL}(n) = \int_{-\infty}^{\theta^H} \pi_i^{L0}\left(Q^L,\theta\right) dF(\theta) + \int_{\theta^H}^{\theta^L} \pi_i^{L0}\left(Q^L,\theta\right) dF(\theta) + \int_{\theta^L}^{\infty} \pi_i^{Ln}\left(X^{SL},\theta\right) dF(\theta) - K\left(X^{SL}/n\right) \quad (29)$$

Notice that the expressions for firms' profits have been expanded, such as to contain both critical demand realizations $\theta^H$ and $\theta^L$. We now show that for any fixed number $n$ of firms, profits are lower in case $SL$ than in case $SH$, i.e. $\pi_i^{SH}(n) \geq \pi_i^{SL}(n)$.

First observe that $\pi_i^{H0}\left(Q^H,\theta\right) > \pi_i^{H0}\left(Q^L,\theta\right)$ for all $\theta < \theta^H$. This follows from the observation that firms are unconstrained at those spot markets, and profits for strategic spot market behavior are higher, than under perfect competition.

In order to compare the remaining terms of expressions (28) and (29), have to make use of the equilibrium conditions derived in theorem 1.[48] We obtain for the remaining three terms of expression (28):

$$\begin{aligned}&\int_{\theta^H}^{\theta^L} \pi_i^{Hn}\left(X^{SH},\theta\right) dF(\theta) + \int_{\theta^L}^{\infty} \pi_i^{Hn}\left(X^{SH},\theta\right) dF(\theta) - K\left(\frac{X^{SH}}{n}\right) = \\ &\int_{\theta^H}^{\infty} -P_q(\cdot)\left(\frac{X^{SH}}{n}\right)^2 + \left(C_q\left(\cdot\right)\frac{X^{SH}}{n} - C\left(\frac{X^{SH}}{n},\theta\right)\right) dF(\theta)) + \left(K_x\left(\cdot\right)\frac{X^{SH}}{n} - K\left(\frac{X^{SH}}{n}\right)\right)\end{aligned} \quad (30)$$

Analogously we rewrite the last three terms of expression (29) and obtain:

$$\begin{aligned}&\int_{\theta^H}^{\theta^L} \pi_i^{L0}\left(Q^L,\theta\right) dF(\theta) + \int_{\theta^L}^{\infty} \pi_i^{Ln}\left(X^{SL},\theta\right) dF(\theta) - K\left(\frac{X^{SL}}{n}\right) = \\ &\int_{\theta^H}^{\theta^L} -P_q(\cdot)\left(\frac{Q^L}{n}\right)^2 + \left(C_q\left(\cdot\right)\frac{Q^L}{n} - C\left(\frac{Q^L}{n},\theta\right)\right) dF(\theta)) + \\ &\int_{\theta^L}^{\infty} -P_q(\cdot)\left(\frac{X^{SL}}{n}\right)^2 + \left(C_q\left(\cdot\right)\frac{X^{SL}}{n} - C\left(\frac{X^{SL}}{n},\theta\right)\right) dF(\theta)) + \left(K_x\left(\cdot\right)\frac{X^{SL}}{n} - K\left(\frac{X^{SL}}{n}\right)\right)\end{aligned} \quad (31)$$

Expressions (30) and (31) can now be compared point wisely for all $\theta > \theta^H$. Observe that $\left(-P_q(Y,\theta)\left(\frac{Y}{n}\right)^2\right)$ is strictly increasing in $Y$ due to assumption 1 (i). Moreover $\left(C_q\left(y\right)y - C\left(y\right)\right)$ and $\left(K_x\left(y\right)y - K\left(y\right)\right)$ are increasing in $y$ due to concavity of production and investment cost (assumptions 1 (ii) and 3). As established in theorem 3, $X^{SL} < X^{SH}$, furthermore, unconstrained production $Q^L$, by definition, is always below the capacity, i.e.

[48] We expand the equilibrium conditions $\int_{\theta^H}^{\infty} P + P_q x_i - C_q dF(\theta) = K_x$ as follows:

$$\int_{\theta^H}^{\infty} P x_i - C\left(x_i\right) dF(\theta) - K\left(x_i\right) = \int_{\theta^H}^{\infty} \left(-P_q x_i + C_q\right) x_i - C\left(x_i\right) dF(\theta) + K_x x_i - K\left(x_i\right).$$

$Q^L \leq X^{SL}$. This directly implies, however, that expression (30) is strictly bigger than expression (31).

We thus established that for a fixed number of firms active on the market, profits of firms are strictly lower in case $SL$ than in case $SH$. That is, when investment is chosen strategically by a fixed number of firms, overall profits are lower under competitive spot markets than for strategic behavior at the spot markets. This implies, furthermore, that in a free entry equilibrium weakly less firms will enter the market in case $SL$ than in case $SH$, i.e. $n^{SL} \leq n^{SH}$.

We finally show that indeed the statements of theorems 3 and 4 are true also under the hypothesis of free entry. From theorem 3 we obtain $X^{SL}\left(n^{SL}\right) \leq X^{SH}\left(n^{SL}\right)$ for some fixed number $n^{SL}$ of firms active in either case. Since under free entry $n^{SL} \leq n^{SH}$ and since investment $X^{SH}$ is increasing in the number of firms active on the market we can directly conclude that $X^{SL}\left(n^{SL}\right) \leq X^{SH}\left(n^{SH}\right)$. The same reasoning holds true for the welfare analysis of theorem 4. We obtained $W^{SL}\left(n^{SL}\right) \leq W^{SH}\left(n^{SL}\right)$ for a fixed number of firms active on the market. Since under free entry $n^{SL} \leq n^{SH}$ and since welfare $W^{SH}$ is increasing in the number of firms active on the market, we can conclude that $W^{SL}\left(n^{SL}\right) \leq W^{SH}\left(n^{SH}\right)$.