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A REAL OPTIONS APPROACH TO DETERMINING POWER PRICES

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Nihat MISIR

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CBS COPENHAGEN BUSINESS SCHOOL
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Nihat MISIR

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"The Doctoral School of Economics and Management is an active national and international research environment at CBS for research degree students who deal with economics and management at business, industry and country level in a theoretical and empirical manner".

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Finally, I would like thank my family for their unwavering support especially when I felt completing this dissertation seemed to be very difficult.

I am solely responsible for any errors in this dissertation.

Nihat MISIR,
Copenhagen, October 2014

Contents

English summary

This dissertation is at the crossroads of electricity markets, industrial organization and real options literature. The main contribution of the dissertation is to investigate the effects of market power when the strategic producers own a portfolio of generation technologies and have ability to affect prices while facing demand or production uncertainties.

The dissertation presents three chapters that deal with the short and long term impacts of market power in the electricity markets. Specifically, the first chapter provides a thorough look at the start up and shut down decisions of the peakload generators and paves way to a better assessment of the extent of the market power of a strategic firm. The second chapter shows the significance of wind power generator ownership on the peakload firms production decisions and market outcomes. Finally, the third chapter investigates how the investment decisions and technology choice differ between fixed and flexible production generators. Overall, this dissertation mainly adopts a real options methodology where the optimal decisions of the producers have a direct impact on the electricity prices contrary to the vast majority of the real options literature.

The first chapter studies the effects of operational characteristics of power plants on optimal dispatch decisions and estimation of market power. Specifically, I give a real options model to show how operational characteristics of power plants and market uncertainty affect start up and shut down decisions. I show that in the case of ownership of multiple generation technologies, optimal dispatch decisions cause capacity withholding for the peakload generator in both the monopoly and the social planner cases. Moreover, the difference between the start up trigger prices for the social planner and the marginal cost reveals significant levels of *real options premium*. Overall, the existence of significant real options premium levels shows that ignoring market uncertainties and operational characteristics of individual generators, results in overestimating the extent of market power of the firms in the industry. Therefore, I conclude that real options analysis can be an asset for more accurate investigations and decisions on the exercise of market power.

The second chapter shifts the focus to the ownership of wind generators as the fixed baseload generation in the first chapter is assumed to be replaced by the stochastic wind generation. Specifically, this chapter investigates the short term effects of wind generator ownership by the owners of fossil-fueled peakload generators. I show that aggregate wind generator ownership reduces the positive impact of the wind generation on the market outcomes and as a result the total peakload production decreases and the market price increases. Furthermore, when all wind generators are owned by the peakload firms, the impact of wind generation on the market outcomes vanishes. Additionally, start up and shut down (suspension) price thresholds are significantly higher when the owner of peakload capacity also owns a share of wind power generators. I also find that a *feed-in premium* support scheme does not affect the peakload firms production levels and hence the market outcomes. However, under a *feed-in tariff* type of support scheme, there is an increase in the total production and a decrease in the market price.

The third chapter, coauthored with Rune Ramsdal Ernstsen, compares the investment timing and the optimal level of investment for a hypothetical monopolist and a social planner that have a one-time opportunity to invest in a generator with either fixed or flexible production. It specifically investigates how the investment triggers, optimal capacities and technology choices change with the changes to the investment cost function, demand uncertainty and the level of installed capacity in the market. The main contribution of this paper is to document that the choice to invest between generators with fixed or flexible production does not only depend on the differences in costs for different technologies but also on the differences in operation of those technologies.

We find that the strategic firm tends to invest at a higher demand trigger level and lower capacity compared to the social planner for both the baseload and the peakload investment cases. Hence, the strategic firm is expected to invest at a later date while incurring lower investment costs. Furthermore, for both the strategic firm and the social planner, fixed baseload generation is preferable during low uncertainty cases whereas high uncertainty tends to result in the choice of flexible peakload generation. We additionally find that highly convex investment costs greatly diminishes the impact of market power on the investment decisions.

Dansk resumé

Denne afhandling befinder sig i krydsfeltet mellem el-markeder, industriøkonomi og real optioner. Afhandlingens væsentligste bidrag er at undersøge effekterne af markedsmagt, n ˚ ar strategiske producenter r ˚ ader over en portefølje af produktionsteknologier og kan p ˚ avirke prisen samtidig med at der er usikkerhed om efterspørgsel eller produktion.

Afhandlingen indeholder tre kapitler, som behandler kort- og langsigtede effekter af markedsmagt i el- markeder. Det første kapitel omhandler en grundig analyse af beslutningerne om at starte og slukke spidsbehandlingsan-læg og baner vejen for en bedre vurdering af den strategiske virksomheds markedsmagt. Det andet kapitel viser betydningen for spidsbelastningsproduktionen og for markedsligevægten af, at spidsbelastningsproducenter ogsåejer vindproduktion. Det tredje kapitel undersøger, hvordan investeringsbeslutninger og teknologivalg bliver p ˚ avirket af, om produktionsteknologierne er fleksible eller ej. I modsætning til hovedparten af litteraturen er afhandlingen overordnet bygget over en real-optionsmetode, hvor producenternes optimale beslutninger påvirker elpriserne.

Det første kapitel undersøger effekterne af elværkernes operationelle karakteristika p ˚ ade optimale opstartsbeslutninger og p ˚ aberegningen af markedsmagt. Specifikt opstiller jeg en real-optionsmodel for at vise, hvordan elværkernes operationelle karakteristika og usikkerhed om markedet p ˚ avirker beslutninger om at starte eller slukke dem. Jeg viser, at hvis el-producenten ejer flere forskellige teknologier til el-produktion, s ˚ avil optimale opstartsbeslutninger for ˚ arsage kapacitetsbegrænsning b ˚ ade for en monopolist og for en samfund-splanlægger, som maksimerer den samlede velfærd. Derudover kan forskellen mellem de priser, der udløser at værket bliver startet op, og marginalomkost-ningen i betydelig grad forklares med et real-options tillæg. Overordnet set viser eksistensen af betydelige real-options tillæg, at man kommer til at overvurdere graden af markedsmagt i branchen, hvis man ikke tager højde for usikkerhed og de individuelle producenters operationelle karakteristika. P ˚ aden baggrund konkluderer jeg, at real-options-analyse kan være et ak-tiv i forhold til mere præcise undersøgelser og beslutninger om udøvelse af markedsmagt.

Det andet kapitel skifter fokus til ejerskab af vindproduktion, idet den faste grundlastproduktion, som blev antaget i første kapitel, her erstattes af stokastisk vindproduktion. Specifikt undersøger dette kapitel de kortsigtede effekter af,

at ejere af spidslastværker, som benytter sig af fossilt brændstof, ogsåejer vindproduktion. Jeg viser, at aggregeret ejerskab til vindproduktion reducerer den positive påvirkning, som vindproduktion har påmarkedsligevægten, og at den totale spidslastproduktion falder, samtidig med at markedsprisen stiger. Derudover viser jeg, at når al vindproduktion ejes af spidslastproducenter, såforsvinder effekten af vindproduktion påmarkedsligevægten. Jo større en del spidslastproducenterne ejer af vindproduktionen, desto højere er opstarts- og nedlukningsgrænserne. Jeg finder også, at hvis vindproduktionen støttes af *feed-in premiums*, såpåvirkes spidslastproduktionen og dermed markedsligevægten ikke, hvorimod der med en *feed-in tariff* vil være en stigning i den samlede produktion og et fald i markedsprisen.

Det tredje kapitel, som er skrevet sammen med Rune Ramsdal Ernstsen, sammenligner investeringernes tidsmæssige placering og deres optimale niveau for henholdsvis en monopolist og en samfundsplanlægger, som har mulighed for en engangsinvestering i enten fast eller fleksibel produktion. Kapitlet undersøger specifikt, hvordan de faktorer, som udløser start eller lukning af spidslastproduktion, de optimale kapaciteter og teknologivalget ændrer sig med ændringer i investeringsomkostningsfunktionen, usikkerhed om efterspørgslen og niveauet for allerede installeret kapacitet i markedet.

Kapitlets væsentligste bidrag er at dokumentere, at valget mellem fast eller fleksibel produktion ikke kun afhænger af de forskellige teknologiers omkostninger, men ogsåpåforskelle i deres måde at fungere på. Vi finder, at den strategiske producent har en tendens til at investere ved et højere niveau for efterspørgslen end samfundsplanlæggeren både for grundlast- og spidslastinvesteringer. Den strategiske producent forventes at investere senere og til lavere investeringsomkostninger sammenlignet med den samfundsmæssige planlægger. Både den strategiske producent og den samfundsmæssige planlægger vil foretrække fast grundlastproduktion, når usikkerheden er lille, mens stor usikkerhed tenderer til at gøre fleksibel spidslastproduktion til det optimale valg. Vi finder endvidere, at stærkt konvekse investeringsomkostninger mindsker markedsmagtens betydning for investeringsbeslutningerne betragteligt.

Introduction

Effects of uncertainty in the electricity markets have been gaining greater attention especially after intermittent renewable generation technologies have started to get significant shares of production in the electricity markets. Many uncertainties (cost, demand, production, price etc.) in electricity markets make the optimal investment and dispatch decisions even more crucial for the strategic producers. The main contribution of the dissertation is to investigate the effects of market power when the strategic producers own a portfolio of generation technologies and have ability to affect prices while facing demand or production uncertainties.

It is broadly accepted in the financial literature that traditional investment decision making methods (e.g. net present value) are not sufficient to capture the accurate value of an irreversible investment that is subject to uncertain costs and/or payoffs. Hence, financial option concept has been applied to real investments to form a new decision making approach that overcomes this problem. As detailed in introductory textbooks Dixit and Pindyck (1994) and Trigeorgis (1996), real options analysis has been used to evaluate a wide range of investment decisions more accurately. Specific examples are; evaluation of natural resources (Brennan and Schwartz (1985), Paddock *et al.* (1988)), real estate developments (Grenadier (1996)), R&D (Miltersen and Schwartz (2003)) and valuation of power plants (Thompson *et al.* (1994), Tseng and Barz (2002)).

In the short term, there are mainly two ways to exercise market power and influence electricity prices for strategic firms. First, firms can decrease the level of output by withholding capacity (Joskow and Kahn, 2002). Second, they expectedly operate their generators for a significantly shorter period of time by asking higher start up and shut down prices than the corresponding socially optimal case. In the long run, the market power could motivate strategic firms to underinvest in generation capacity, delay the investment decision or choose to invest in a specific type of technology.

This dissertation presents three chapters that deals with the short and long term impacts of market power in the electricity markets. All three chapters have very close setups (in terms of electricity generation portfolio, nature of the stochastic process, parameter values etc.) to present different aspects of exercise of market power in a simplified electricity market. This approach links all three chapters and helps us to get a relatively unified picture on the related short and long term decisions of the strategic firms. Specifically, the first chapter provides a thorough look at the start up and shut down decisions of the peakload generators and paves way to a better assessment of the extent of the market power of a strategic firm. The second chapter shows the significance of wind power generator ownership on the peakload firms production decisions and market outcomes. Finally, the third chapter investigates how the investment decisions and technology choice differ between fixed and flexible production generators. Overall, this dissertation mainly adopts a real options methodology where the optimal decisions of the producers have a direct impact on the electricity prices contrary to the vast majority of the real options literature.

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Effects of Power Plant Operational Characteristics on Capacity Withholding and Estimation of Market Power

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May 2015

Abstract

In this paper, I study the effects of operational characteristics of power plants on optimal dispatch decisions and estimation of market power. I give a real options model to show how operational characteristics of power plants and market uncertainty affect start up and shut down decisions. In the model, the industry adjusts its production or take start up and shut down decisions for power plants according to realization of industry-wide exogenous demand shocks. I show that in the case of ownership of multiple generation technologies, optimal dispatch decisions causes capacity withholding for the peakload generator in both the monopoly and the social planner cases. Moreover, the difference between the start up trigger prices for the social planner and the marginal cost reveals significant levels of *real options premia*. I further find that *real options premium* explains more than 24% of the monopolist's mark-up. To make use of this finding, I provide an adjustment to the Lerner Index by incorporating *real options premium* into its formula. Furthermore, I show

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that flexible peakload generation helps to lower *real options premium* levels for the social planner and the extent of market power for the monopolist by lowering optimal start up trigger levels.

Keywords: Uncertainty, real options, electricity.

JEL Classification: D92, L4, L11, L12, L94

1 Introduction and Literature Review

In this paper, I study the effects of operational characteristics of power plants on optimal dispatch decisions and estimation of market power. I show how optimal operation of power plants leads to capacity withholding decisions for both a monopolist and a social planner. In that regard, I combine two strands of literature. First, the electricity markets literature regarding the exercise of unilateral market power. Second, the real options literature on irreversible investment under uncertainty.

In the two strands of literature mentioned above, there is not a theoretical model showing the effects of operational characteristics of power plants on capacity withholding decisions. Therefore, the first aim of this paper is to bridge these two strands of literature by giving a theoretical model to show how market uncertainty and operational characteristics of the power plants affect the extent of *economic* capacity withholding. I further compare the monopolist and social planner cases to provide a more accurate measure for the extent of market power of the monopolist. To achieve this goal, I calculate the social planner's mark-up (prior to starting up its peakload generator) and isolate it from the corresponding monopolist's mark-up.

As suggested by Møllgaard and Nielsen (2004), by including demand uncertainty into the model, I use real options analysis to determine optimal dispatch decisions of generators facing start up and shut down costs. I find the thresholds where peakload generators start up and shut down (suspend) production. I interpret the difference between the start up price threshold and the marginal cost as a measure of the extent of economic capacity withholding. Furthermore I show that, even for the case of social planner, a certain level of capacity withholding is unavoidable. This result leads to a reinterpretation of the Lerner Index that takes *real options premium* into account.

Economic capacity withholding can be defined as reducing output by asking for higher prices or submitting higher bids than the marginal cost of the generator in question (Twomey *et al.* (2005)). Harvey and Hogan (2001) describe the Federal Energy Regulatory Commission's (an independent agency that regulates the interstate transmission of electricity, natural gas, and oil in the U.S.) economic withholding criterion as; *during periods of high demand and high market prices, all generation capacity whose incremental costs do not exceed the market price would be either producing energy or supplying operating reserves.*[1] They further discuss the effects of start up and minimum load costs by noting: *In markets in which generators have start-up costs, minimum load costs and operating flexibilities, conclusions regarding the exercise of market power cannot be drawn based on a comparison of prices and incremental costs of off-line units.* As a result, they indicate that even if price levels are above marginal cost of production, a generator might not be dispatched because of the existence of start up costs. This is simply because, marginal costs do not reflect the total incremental costs that are incurred by the firm to start the production. On this point, Brennan (2003) also underlines that *the need to recover fixed costs can lead the prices substantially above average costs in peak periods.*

Focusing on the electricity literature, strategic actions of the producers have been a long lasting interest of researchers and policy makers. Mainly focused on the California electricity market crisis in the summer of 2000 Harvey and Hogan (2001) discuss regulatory and economic aspects of capacity withholding, Joskow and Kahn (2002) identify the existence of capacity withholding in certain hours, Borenstein *et al.* (2002) find the existence of anti-competitive pricing during peak demand hours and Wolak (2003) gives a measure for unilateral market power for the California market using actual submitted bids. Apart from the California market, Wolfram (1998) studies strategic bidding behaviours in England and Wales.

On the valuation and optimal operation of generation technologies, Gardner and Zhuang (2000) study a short term and discrete-time real options model for power plant valuation under some operational constraints, including start up costs and minimum generation levels. By using New England power pool data, they calculate that operating constraints (specifically, minimum

[1]Based on this criterion, any generation capacity is considered to be economically withheld if it has not been dispatched yet while the market price is above its marginal cost.

generation levels) can have a significant effect on power plant valuation. Deng and Oren (2003) also use a real options based valuation for power plants by incorporating start up and shut down costs. They use price and cost uncertainties in their analysis and conclude that start up costs reduce the real options-based value of a power plant. Furthermore, they show that, under the mean-reversion models for prices, ignoring start up costs alone can explain a sizeable portion of the overstated capacity value of a power plant. Thompson *et al.* (2003) also study the valuation and optimal operation of hydroelectric and thermal power plants. They provide a model determining the optimal operating strategy of power plants as well as evaluating economic trade-offs involved in building new facilities.

The model I present is an extension of the existing real options literature in several ways. In standard real options analysis (specifically on electricity markets), there is not a paper taking both operational constraints for power plant operations and endogenous market price mechanisms into account. Furthermore the existing models are generally based on ownership of a single power plant under exogenous price processes (*e.g.,* Thompson *et al.* (2003)). In the light of existing real options and electricity literatures, I will give a model that incorporates ownership of multiple generators subject to a number of operational constraints (total capacity, minimum operation level, flexibility in production, start up and shut down costs) and ability to affect market prices with optimal dispatch decisions (start up, shut down decisions and optimal production levels) in continuous time.

The rest of the paper is organized as follows: In section 2, I give the aim and formal set up with a sample deterministic case. In section 3, I provide model derivations for the monopolist case. In section 4, I adopt the model to the corresponding social planner's problem to set a benchmark and distinguish the effects of market power by calculating the *real options premium.* In section 5, I give numerical results to the theoretical derivations of Section 3 and 4. In section 6, I provide a brief conclusion on my findings.

2 The Aim and Model Set up

In this paper, I present a continuous time real options model as I consider start up and shut down costs as prospective sunk costs (Pindyck (2008)) and, as a result, take the partial irreversibility of start up and shut down decisions into account. In this model, I combine Dixit and Pindyck (1994)'s optimal switching approach and Hagspiel *et.al.* (2010)'s flexible production under uncertainty approach (see also Dangl (1999)). I use this optimal switching approach to show the effects of start up and shut down costs (alongside total capacity, production flexibility, minimum operating levels and uncertainty) on the optimal operation of a peakload generator under the ownership of a generation portfolio.[2] A main property of the model is focusing on ownership of two different generation technologies either by the monopolist or by a social planner. I make this assumption to investigate a more realistic scenario than the existing real options models in the literature since ownership of multiple generation technologies is a common feature in the electricity industries.

The industry consists of two types of electricity generation technologies. For simplification, I assume that there is only one *baseload* (B) and one *peakload* (P) generation unit. I will investigate the cases for both flexible and inflexible peakload generation. Furthermore in this model, optimal switching means utilizing only the baseload generator or switching on the peakload generator to utilize both of them. In other words, switching on the peakload generator does not mean shutting down the baseload generator.

Each generation unit is characterized by $(K_i, I_i, E_i, c_i, \overline{q}_i)$ for $i = B, P$; where generation units have maximum capacity K_i, start up cost I_i, shut down (suspension of production) cost E_i and constant marginal cost of production c_i.[3] In addition, in the case of flexible production, $\overline{q}_i$ shows the minimum possible operation level of the active generator i. Therefore, at each instant in time, the production level $q_i(t)$ of the active flexible generator i satisfies: $0 \leq \overline{q}_i \leq q_i(t) \leq K_i$.[4]

Generators have infinite lifetime and they are differentiated such that $I_B > I_P$ and $c_P > c_B = 0$. This assumption is in line with the electricity literature where peakload generators are expected to have higher marginal cost and lower start up cost (e.g. Joskow (2006)). I further assume that there are no

[2]In this paper, I am not concerned with either the initial investment problem for the existing generators or investment in new generators.

[3]Start up and shut down costs may actually depend on several parameters including: technology, total capacity and total off/on-time of the generators (Harvey and Hogan (2001)). However since I assume to have predetermined capacities and technologies, I will also treat start up and shut down costs as constants.

[4]Minimum operation level is a technological constraint and could be as small as the generation technology requires.

transmission costs and generators can adjust their output without a cost.

The problem is to solve for the optimal operation of the peakload generator under the ownership of multiple generation technologies. In actual electricity markets, firms operate their baseload generators almost throughout the year without shutting them down and start peakload generators whenever the market demand is high enough. Since capacity withholding is more likely to happen using the more expensive peakload generators, I will assume that the monopolist (or the social planner) always keeps the baseload generator operational[5] and at all times the baseload generator operates at full capacity, $q_B(t) = K_B$.[6] Hence, we focus on the optimal operation of the peakload generator.

At time t, the monopolist produces $Q(t) = K_B + q_P(t)$ units of output and depending on the maximum installed capacity, total industry production satisfies: $K_B + K_P \geq Q(t) \geq K_B$ for all t. The price of electricity fluctuates stochastically according to an inverse demand function:

$$P(t) = D[X(t), Q(t)] \tag{1}$$

where $D : R_+ \to R$ is a twice continuously differentiable inverse demand function with $\partial D/\partial X > 0$ and $\partial D/\partial Q < 0$. To simplify model derivations, I will further assume to have a linear inverse demand function:

$$P(t) = X(t) - \gamma Q(t) \quad \text{with } \gamma > 0. \tag{2}$$

$X(t)$ is the exogenous demand shock following a *Geometric Brownian Motion* z [7]:

$$dX(t) = \alpha X(t)dt + \sigma X(t)dz \tag{3}$$

[5]This assumption can also be justified by very high start up costs for baseload generators. If the firm shut downs the baseload generator, it will have to incur a very high start up cost to restart the generator in the future. Furthermore, zero marginal cost assumption is also in favour of this assumption.

[6]The fixed baseload generation assumption can be relaxed to have a flexible baseload generation for a more realistic scenario but it would also give rise to more complicated equations without qualitatively changing the results in our basic model.

[7]Linear demand function and Geometric Brownian Motion assumptions are widely-used in the electricity real options literature (e.g. Aguerrevere (2005)). Additionally, Marathe and Ryan (2005) show that the US monthly consumption data of electricity pass the tests for not contradicting a Geometric Brownian Motion process after deseasonalization.

where α is the drift paramater, σ is the volatility parameter, dt is the increment of time and dz is the increment of a Wiener process.

The state of the industry is characterized by $[X(t), K_B + q_P^*(t), \omega]$ where $q_P^*(t)$ is the optimal level of peakload production at time t and ω is the indication of whether the peakload generator is active. In general, the peakload generator will be started when demand is high and it will be shut down when demand is low enough. Specifically, in state $[X(t), K_B, 0]$ the peakload generator will be started when $X(t) \geq X_H$ by incurring the start up cost I_P. In state $[X(t), K_B + q_P^*(t), 1]$, the peakload generator will be shut down when $X(t) \leq X_L$ by incurring the shut down cost E_P.

2.1 A Deterministic Case

In this section, I give the evolution of total industry production given a deterministic evolution of demand shock, $X(t)$. The purpose of this section is to show how demand affects the optimal operation of a flexible peakload generator and hence total industry production. I assume that at $t = 0$, the baseload generator is being operated at full capacity whereas the peakload generator has not been started up, yet.

For the sample case given in **Figure 1**, the demand shock starts at a point below the start up trigger level of the peakload generator. Afterwards, the demand shock linearly increases until $t = 125$. At $t = 125$ point, it starts to linearly decrease. Furthermore, I assume that $t = 50$ is when the demand shock hits the trigger start up level (X_H) whereas $t = 200$ is when it hits the trigger shut down demand shock level (X_L).

Given this deterministic case, the evolution of the monopolist's total production (under flexible peakload generation) is pictured in **Figure 2**. Looking at the **Figure 2**, one can chronologically observe that:

- The monopolist operates only the baseload generator until the demand shock hits the start-up trigger when $t = 50$.
- At $t = 50$, the monopolist starts up the peakload generator at the minimum operation level, $\overline{q}_P$.
- Between $t = 50$ and $t = 100$, due to increasing demand, the monopolist first continues to produce at the minimum operation level and

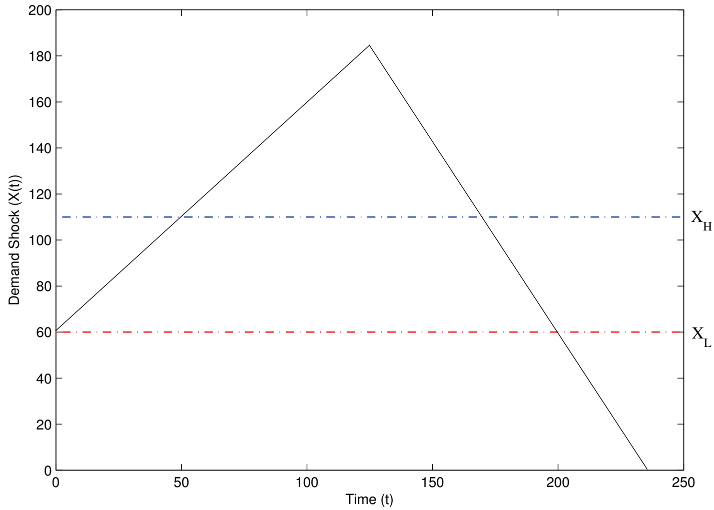

Figure 1: *Sample Evolution of the Demand Shock $X(t)$.*

then keeps increasing the total output by ramping up the peakload generator.

- At $t = 100$, the monopolist starts to operate the peakload generator at full capacity, K_P.
- At $t = 150$, due to declining demand, the monopolist starts to decrease the production of the peakload generator.
- Between $t = 150$ and $t = 200$, due to declining demand, the monopolist keeps decreasing the total output until it starts to operate at the minimum level.
- At $t = 200$, the monopolist shuts down the peakload generator.

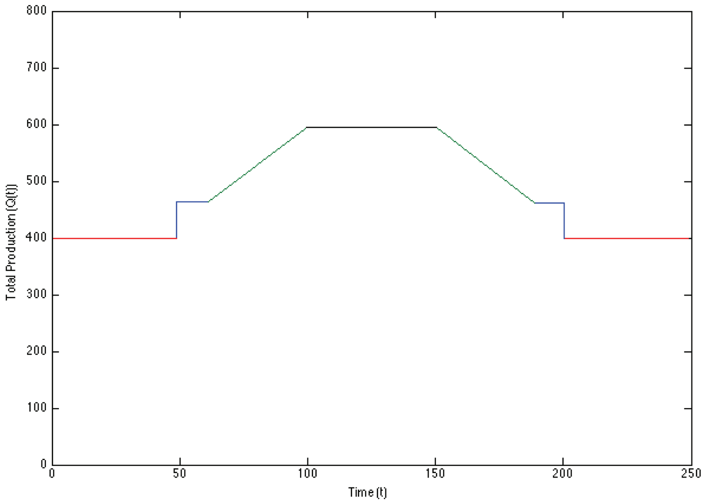

Figure 2: *Sample Evolution of Total Production $Q(t)$ (For $\overline{q}_P = 40$, $K_B = 400$ and $K_P = 200$)*

3 Monopolist Production

The monopolist's objective is to maximize the total discounted value of its generation portfolio. To achieve this objective, the monopolist decides when to optimally start up and shut down peakload production. Therefore, there will be two possible types of profit flows. First, the profit flow when only the baseload generator is active, and second, the profit flow when both of the generators are active. According to the demand shock level, the monopolist faces start up and shut down costs as well as the cost of electricity production for its peakload generator. In this section, I will investigate the possible profit functions and optimal production levels by focusing on flexibility of the peakload production.

3.1 Fixed Peakload Generation

In this case, I assume that peakload production is fixed and at full capacity when it is active. Therefore, total industry production simply depends on whether the peakload generator is active or not. In that regard, baseload-only production takes place when demand is low enough and there is no need for peakload generation. For baseload-only production, when $\omega = 0$, the profit function of the monopolist is:

$$\Pi^B[X(t), K_B] = [X(t) - \gamma K_B]K_B \tag{4}$$

On the other hand, the peakload generator is started up when demand is high enough. In that case, when $\omega = 1$, the profit function of the monopolist is:

$$\Pi^{B+P}[X(t), K_B + K_P] = [X(t) - \gamma(K_B + K_P)](K_B + K_P) - c_P K_P \tag{5}$$

3.2 Flexible Peakload Generation

In this section, I relax the fixed peakload production assumption. For this case, baseload-only production still yields the same profit function for the monopolist as the fixed peakload production case. However, when the peakload generator is active, the profit function depends on the optimal production of the peakload generator (which is now flexible). Therefore, the profit function of the monopolist when the peakload generator is active, $\omega = 1$, is:

$$\Pi^{B+P}[X(t), K_B+q_P^*(t)] = sup_{q_P(t)}\{[X(t)-\gamma(K_B+q_P(t))](K_B+q_P(t))-c_P q_P(t)\} \tag{6}$$

s.t. $\overline{q}_P(t) \leq q_P(t) \leq K_P$.

Remark 1. *: When the peakload generator is active (i.e., $q_P(t) > 0$) this state will negatively affect the profits coming from baseload generation since the price will fall when total market output increases ($\partial D/\partial Q < 0$). This affect is the opportunity cost of starting up the peakload generator.*

Depending on demand shock levels, optimal production of the flexible peakload generator consists of three parts. First, the peakload generator is operating at minimum level. Second, the peakload generator is operating between minimum and maximum levels. Third, the peakload generator is operating at full capacity.

Using **Equation 6**, optimal peakload production levels for the monopolist are:

$$q_P^*(t) = \begin{cases} 0 & \text{if } X < X_L^M \\ \overline{q}_P & \text{if } \underline{X}^M > X \geq X_L^M \\ \dfrac{X(t) - c_P}{2\gamma} - K_B & \text{if } \overline{X}^M > X \geq \underline{X}^M \\ K_P & \text{if } X \geq \overline{X}^M \end{cases} \quad (7)$$

where formal definitions of the trigger demand shock levels: X_L^M, $\underline{X}^M$ and $\overline{X}^M$ are presented in the following section.

3.3 Real Options Set-up

Given the initial state of the economy, $[X_0, K_B, \omega = 0]$, let $V^0[X(t), K_B]$ denote the expected net present value of the generation portfolio when the peakload generator is idle with optimal future strategies. Similarly, $V^1[X(t), K_B + q_P^*(t)]$ is the expected net present value of the generation portfolio when the peakload generator is active with optimal future strategies. By using dynamic programming, $V^0[X(t), K_B]$ can be expressed as the sum of the operating profit over the interval $(t, t+dt)$ and the continuation value beyond $(t, t+dt)$, i.e.,

$$V^0[X(t), K_B] = \Pi^B[X(t), K_B]dt + E\left[e^{-rdt}V^0[X(t) + dX(t), K_B]\right]$$

Using standard real options techniques (i.e., using Ito's Lemma to expand the right hand side and then neglecting the terms that go to zero), $V^0[X(t), K_B]$ will be the solution to the ordinary differential equation (see, Dixit and Pindyck (1994), Chp. 6):

$$\frac{1}{2}\sigma^2 X(t)^2 V_{XX}^0 + \alpha X(t) V_X^0 - rV^0 + \Pi^B[X(t), K_B] = 0 \quad (8)$$

Similarly, , $V^1[X(t), K_B + q_P^*(t)]$ will be the solution to the ordinary differential equation:

$$\frac{1}{2}\sigma^2 X(t)^2 V^1_{XX} + \alpha X(t) V^1_X - rV^1 + \Pi^{B+P}[X(t), K_B + q^*_P(t)] = 0 \quad (9)$$

Since there are different profit functions depending on the flexibility of the peakload generator, the solutions to the above ordinary differential equations change with those profit functions. Below, I show how those different profit functions affect the corresponding value functions.

3.3.1 Value Function for Fixed Peakload Generation

Depending on the previously given profit functions, value functions for the fixed peakload production case are:

$$V^0 = \begin{cases} A_1 X^{\beta_1} + \frac{K_B}{r-\alpha}X - \frac{\gamma K_B^2}{r} & \text{if } X < X_H^M \\ F_2 X^{\beta_2} + \frac{K_B+K_P}{r-\alpha}X - \frac{\gamma(K_B+K_P)^2 + c_P K_P}{r} - I_P & \text{if } X \geq X_H^M \end{cases}$$

and

$$V^1 = \begin{cases} A_1 X^{\beta_1} + \frac{K_B}{r-\alpha}X - \frac{\gamma K_B^2}{r} - E_P & \text{if } X \leq X_L^M \\ F_2 X^{\beta_2} + \frac{K_B+K_P}{r-\alpha}X - \frac{\gamma(K_B+K_P)^2 + c_P K_P}{r} & \text{if } X > X_L^M \end{cases}$$

Definition 2. *For the monopolist, under fixed peakload production, formal definitions of the trigger levels X_H^M and X_L^M are given by:*

$$X_H^M = inf\left\{X(t)|\omega = 0 \wedge V^1[X(t), K_B + K_P] - I_P \geq V^0[X(t), K_B], \forall t\right\} \quad (10)$$

$$X_L^M = sup\left\{X(t)|\omega = 1 \wedge V^0[X(t), K_B] - E_P \geq V^1[X(t), K_B + K_P], \forall t\right\} \quad (11)$$

By using value matching and smooth-pasting conditions, there will be four equations and four unknowns (A_1, F_2, X_L^M and X_H^M). Given the nature of the value functions, numerical solutions for the trigger levels X_L^M and X_H^M exist but they cannot be derived analytically (Dixit 1989). I provide numerical solutions to this problem in **Section 5**.

3.3.2 Value Function for Flexible Peakload Generation

Depending on the previously given profit functions, value functions for the flexible peakload production case are:

$$V^0 = \begin{cases} A_1 X^{\beta_1} + \frac{K_B}{r-\alpha} X - \frac{\gamma K_B^2}{r} & \text{if } X < X_H^M \\ V^1 - I_P & \text{if } X \geq X_H^M \end{cases}$$

and

$$V^1 = \begin{cases} A_1 X^{\beta_1} + \frac{K_B}{r-\alpha} X - \frac{\gamma K_B^2}{r} - E_P & \text{if } X \leq X_L^M \\ C_1 X^{\beta_1} + C_2 X^{\beta_2} + \frac{K_B + \overline{q}_P}{r-\alpha} X - \frac{\gamma (K_B + \overline{q}_P)^2 + c_P \overline{q}_P}{r} & \text{if } \underline{X}^M \geq X > X_L^M \\ D_1 X^{\beta_1} + D_2 X^{\beta_2} + \frac{1}{4\gamma} \left[\frac{X^2}{r - 2\alpha - \sigma^2} - \frac{2 c_P}{r-\alpha} X + \frac{c_P^2}{r} \right] + \frac{c_P K_B}{r} & \text{if } \overline{X}^M \geq X > \underline{X}^M \\ F_2 X^{\beta_2} + \frac{K_B + K_P}{r-\alpha} X - \frac{\gamma (K_B + K_P)^2 + c_P K_P}{r} & \text{if } X > \overline{X}^M \end{cases}$$

where $\underline{X}^M = [2\gamma(K_B + \overline{q}_P) + c_P]$ and $\overline{X}^M = [2\gamma(K_B + K_P) + c_P]$.

Definition 3. *For the monopolist, under flexible peakload production, formal definitions of the trigger levels X_H^M, X_L^M, $\underline{X}^M$ and $\overline{X}^M$ are given by:*

$$X_H^M = inf\left\{X(t)|\omega = 0 \wedge V^1[X(t), K_B + \overline{q}_P] - I_P \geq V^0[X(t), K_B], \forall t\right\} \tag{12}$$

$$X_L^M = sup\left\{X(t)|\omega = 1 \wedge V^0[X(t), K_B] - E_P \geq V^1[X(t), K_B + \overline{q}_P], \forall t\right\} \tag{13}$$

$$\underline{X}^M = sup\left\{X(t)|\omega = 1 \wedge \Pi^{B+P}[X(t), K_B + q_P^*(t)] = \Pi^{B+P}[X(t), K_B + \overline{q}_P], \forall t\right\} \tag{14}$$

$$\overline{X}^M = inf\left\{X(t)|\omega = 1 \wedge \Pi^{B+P}[X(t), K_B + q_P^*(t)] = \Pi^{B+P}[X(t), K_B + K_P], \forall t\right\} \tag{15}$$

By using value matching and smooth-pasting conditions, there will be eight equations and eight unknowns (A_1, C_1, C_2, D_1, D_2, F_2, X_L^M and X_H^M). Given the nature of the value functions, numerical solutions for the trigger levels X_L^M and X_H^M exist but they cannot be derived analytically. I provide numerical solutions to this problem in **Section 5**.

4 Social Planning and Competitive Equilibrium

In this section, I investigate the social planner's problem. The aim is to show that, with the same set up as the monopolist, the social planner's optimal actions result in a certain level of economic capacity withholding too. Afterwards, I compare the monopolist and social planner cases to provide a more accurate measure for the extent of market power of the monopolist. To achieve this goal, I calculate the social planner's mark-up (prior to starting up its peakload generator) and isolate it from the corresponding monopolist's mark-up.

In the social planner's problem, total discounted expected social surplus is to be maximized. In that regard, I use the same approach as Dixit and Pindyck (1994, Chapter 9). First, I define the area under the demand curve for a given production level, $Q(t)$, by:

$$U[X(t), Q(t)] = \int_0^{Q(t)} D[X(t), Q(t)]dq = \int_0^{Q(t)} (X - \gamma q)dq = XQ(t) - \frac{\gamma Q(t)^2}{2} \tag{16}$$

Then the total social surplus for a given production level, $Q(t)$, is:

$$S^{\omega}[X(t), Q(t)] = max_Q \left\{U[X(t), Q(t)] - C^{\omega}[Q(t)]\right\} \tag{17}$$

where superscript $\omega = 0, 1$ shows whether both of the generators are online, and $C^{\omega}[Q(t)]$ denotes the total cost of current production. In this setup instantaneous social surplus at time t, $S^{\omega}[X(t), Q(t)]$, will replace the profit flow of a firm. Therefore, derivations will follow the same steps as the case of the monopolist. Below, I give how the total social surplus is affected by the flexibility of the peakload production.

4.1 Fixed Peakload Production

Similar to the monopoly case, baseload-only production takes place when demand is low enough and there is no need for peakload generation. For baseload-only production, when $\omega = 0$, the total social surplus is:

$$S^0[X(t), K_B] = XK_B - \frac{\gamma K_B^2}{2}$$

On the other hand, the peakload generator is started up when demand is high enough. In that case, when $\omega = 1$, the total social surplus is:

$$S^1[X(t), K_B + K_P] = X(K_B + K_P) - \frac{\gamma(K_B + K_P)^2 + 2c_P K_P}{2}$$

4.2 Flexible Peakload Production

The approach for finding the total social surplus will be similar to the monopoly case. Baseload-only production still yields the same total social surplus as the fixed peakload production case. However, flexible peakload production entails the following total social surplus when $\omega = 1$:

$$S^1[X(t), K_B + q_P^*(t)] = sup_{q_P(t)}\{X[K_B + q_P(t)] - \frac{\gamma(K_B + q_P(t))^2 + 2c_P q_P(t)}{2}\}$$

s.t. $\overline{q}_P(t) \leq q_P(t) \leq K_P$.

Again similar to the monopoly case, the optimal production of the social planner consists of three parts. In that regard, optimal production levels for flexible peakload production are given by:

$$q_P^*(t) = \begin{cases} 0 & \text{if } X < X_L^{SP} \\ \overline{q}_P & \text{if } \underline{X}^{SP} > X \geq X_L^{SP} \\ \dfrac{X(t) - c_P}{\gamma} - K_B & \text{if } \overline{X}^{SP} > X \geq \underline{X}^{SP} \\ K_P & \text{if } X \geq \overline{X}^{SP} \end{cases} \tag{18}$$

where formal definitions of the trigger demand shock levels: X_L^{SP}, $\underline{X}^{SP}$ and $\overline{X}^{SP}$ are presented in the following section.

4.3 Real Options Set-up

Using standard real options analysis as before, and given the initial state of the economy $[X_0, K_B, \omega = 0]$, let $W^0[X(t), K_B]$ denote the expected net present value of the total social surplus when the peakload generator is idle with optimal future strategies. Similarly, $W^1[X(t), K_B + q_P^*(t)]$ is the expected net present value of the total social surplus when the peakload generator is active with optimal future strategies. Using standard real options techniques, $W^0[X(t), K_B]$ will be the solution to the ordinary differential equation:

$$\frac{1}{2}\sigma^2 X(t)^2 W_{XX}^{\omega} + \alpha X(t) W_X^{\omega} - rW^{\omega} + S^0[X(t), K_B] = 0 \text{ for } \omega = 0, 1 \quad (19)$$

Similarly, $W^1[X(t), K_B + q_P^*(t)]$ will be the solution to the ordinary differential equation:

$$\frac{1}{2}\sigma^2 X(t)^2 W_{XX}^{\omega} + \alpha X(t) W_X^{\omega} - rW^{\omega} + S^1[X(t), K_B + q_P^*(t)] = 0 \text{ for } \omega = 0, 1 \quad (20)$$

4.3.1 Value Function for Fixed Peakload Generation

Depending on the previously given social welfare functions, value functions for the fixed peakload production case are:

$$W^0 = \begin{cases} G_1 X^{\beta_1} + \frac{K_B}{r-\alpha} X - \frac{\gamma K_B^2}{2r} & \text{if } X < X_H^{SP} \\ N_2 X^{\beta_2} + \frac{K_B + K_P}{r-\alpha} X - \frac{\gamma (K_B + K_P)^2 + 2c_P K_P}{2r} - I_P & \text{if } X \geq X_H^{SP} \end{cases}$$

and

$$W^1 = \begin{cases} G_1 X^{\beta_1} + \frac{K_B}{r-\alpha} X - \frac{\gamma K_B^2}{2r} - E_P & \text{if } X \leq X_L^{SP} \\ N_2 X^{\beta_2} + \frac{K_B + K_P}{r-\alpha} X - \frac{\gamma (K_B + K_P)^2 + 2c_P K_P}{2r} & \text{if } X > X_L^{SP} \end{cases}$$

Definition 4. *For the social planner, under fixed peakload production, formal* *definitions of the trigger levels X_H^{SP} and X_L^{SP} are given by:*

$$X_H^{SP} = inf\left\{X(t)|\omega = 0 \wedge W^1[X(t), K_B + K_P] - I_P \geq W^0[X(t), K_B], \forall t\right\} \tag{21}$$

$$X_L^{SP} = sup\left\{X(t)|\omega = 1 \wedge W^0[X(t), K_B] - E_P \geq W^1[X(t), K_B + K_P], \forall t\right\} \tag{22}$$

By using value matching and smooth-pasting conditions, there will be four equations and four unknowns (G_1, N_2, X_L^{SP} and X_H^{SP}). Given the nature of the value functions, solutions for the trigger levels X_L^{SP} and X_H^{SP} exist but they cannot be derived analytically. I provide numerical solutions to this problem in **Section 5**.

4.3.2 Value Function for Flexible Peakload Generation

Depending on the previously given social welfare functions, value functions for the flexible peakload production case are:

$$W^0 = \begin{cases} G_1 X^{\beta_1} + \frac{K_B}{r-\alpha}X - \frac{\gamma K_B^2}{2r} & \text{if } X < X_H^{SP} \\ W^1 - I_P & \text{if } X \geq X_H^{SP} \end{cases}$$

and

$$W^1 = \begin{cases} G_1 X^{\beta_1} + \frac{K_B}{r-\alpha}X - \frac{\gamma K_B^2}{2r} - E_P & \text{if } X \leq X_L^{SP} \\ J_1 X^{\beta_1} + J_2 X^{\beta_2} + \frac{K_B + \overline{q}_P}{r-\alpha}X - \frac{\gamma(K_B+\overline{q}_P)^2 + 2c_P\overline{q}_P}{2r} & \text{if } \underline{X}^{SP} \geq X > X_L \\ M_1 X^{\beta_1} + M_2 X^{\beta_2} + \frac{1}{2\gamma}\left[\frac{X^2}{r-2\alpha-\sigma^2} - \frac{2c_P}{r-\alpha}X + \frac{c_P^2}{r}\right] + \frac{c_P K_B}{r} & \text{if } \overline{X}^{SP} \geq X > \underline{X}^{SP} \\ N_2 X^{\beta_2} + \frac{K_B+K_P}{r-\alpha}X - \frac{\gamma(K_B+K_P)^2 + 2c_P K_P}{2r} & \text{if } X > \overline{X}^{SP} \end{cases}$$

where $\underline{X}^{SP} = [\gamma(K_B + \overline{q}_P) + c_P]$ and $\overline{X}^{SP} = [\gamma(K_B + K_P) + c_P]$.

Definition 5. *For the social planner, under flexible peakload production, formal definitions of the trigger levels X_H^{SP}, X_L^{SP}, $\underline{X}^{SP}$ and $\overline{X}^{SP}$ are given by:*

$$X_H^{SP} = inf\left\{X(t)|\omega = 0 \wedge W^1[X(t), K_B + \overline{q}_P] - I_P \geq W^0[X(t), K_B], \forall t\right\} \tag{23}$$

$$X_L^{SP} = sup\left\{X(t)|\omega = 1 \wedge W^0[X(t), K_B] - E_P \geq W^1[X(t), K_B + \overline{q}_P], \forall t\right\} \quad (24)$$

$$\underline{X}^{SP} = sup\left\{X(t)|\omega = 1 \wedge S^1[X(t), K_B + q_P^*(t)] = S^1[X(t), K_B + \overline{q}_P], \forall t\right\} \quad (25)$$

$$\overline{X}^{SP} = inf\left\{X(t)|\omega = 1 \wedge S^1[X(t), K_B + q_P^*(t)] = S^1[X(t), K_B + K_P], \forall t\right\} \quad (26)$$

By using value matching and smooth-pasting conditions, there will be eight equations and eight unknowns (G_1, J_1, J_2, M_1, M_2, N_2, X_L^{SP} and X_H^{SP}). Given the nature of the value functions, solutions for the trigger levels X_L^{SP} and X_H^{SP} exist but they cannot be derived analytically. I provide numerical solutions to this problem in **Section 5**.

5 Numerical Results

In this section, I give numerical results to the theoretical derivations of **Section 3** and **4**. As mentioned previously, solutions to the corresponding systems of equations can only be derived numerically (see **Appendix**). In my benchmark simulation, I take values for the initial model parameters as, $\alpha = 0.01$, $\sigma = 0.1$, $r = 0.05$, $\gamma = 0.1$, $c_P = 50$, $\overline{q}_P = 40$, $K_B = 400$ and $K_P = 200$.

5.1 Fixed Peakload Production

Table 1: *Trigger Levels for Fixed Peakload Production*

K_P	I_P	E_P	X_H^M	X_H^{SP}	X_L^M	X_L^{SP}	$\frac{X_H^M - X_H^{SP}}{X_H^M}$
200	0	0	127.296	100.00	127.296	100.00	0.214
200	1000	0	159.626	107.389	140.631	92.869	0.3272
200	1000	1000	161.999	109.181	138.016	90.837	0.326
400	1000	1000	180.318	117.731	159.689	102.276	0.347

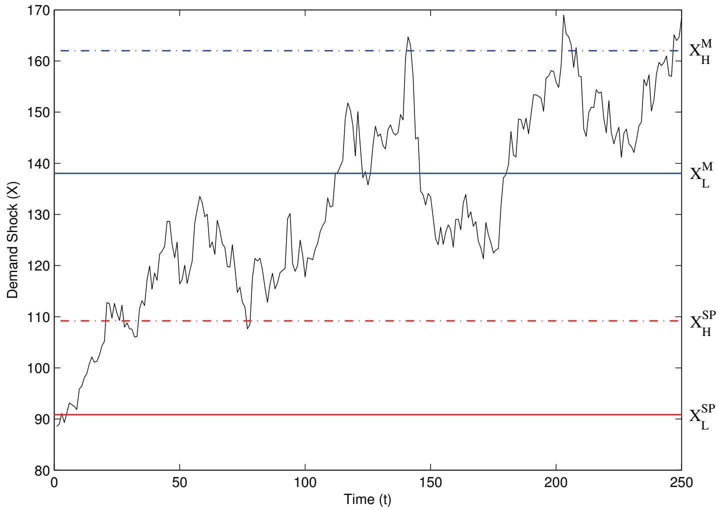

Figure 3: *Startup and Shutdown Thresholds for Fixed Peakload Production (For $K_P = 200$, $I_P = 1000$ and $E_P = 1000$)*

5.2 Flexible Peakload Production

Table 2: *Trigger Levels for Flexible Peakload Production*

$\overline{q}_P$	I_P	E_P	X_H^M	X_H^{SP}	X_L^M	X_L^{SP}	$\frac{X_H^M - X_H^{SP}}{X_H^M}$
40	0	0	105.982	92.00	105.982	92.00	0.1318
40	1000	0	149.905	104.595	119.401	80.7211	0.302
40	1000	1000	153.395	107.222	114.747	76.9399	0.301
80	1000	1000	153.53	107.383	122.526	81.9803	0.301

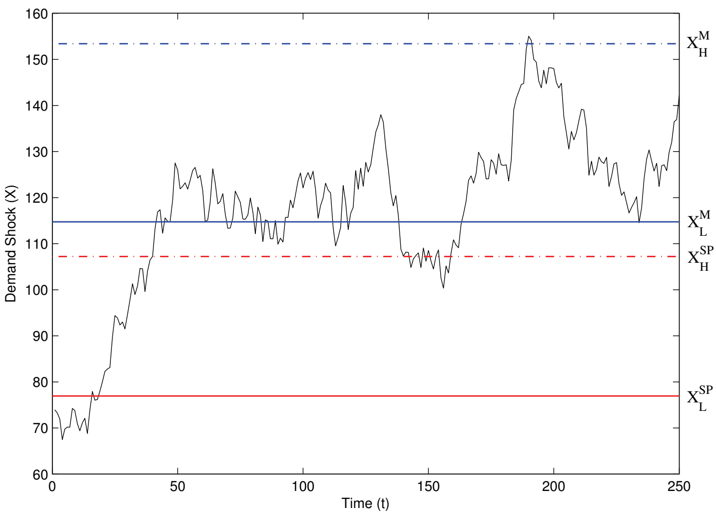

Figure 4: *Startup and Shutdown Thresholds for Flexible Peakload Production (For $\overline{q}_P = 40$, $K_P = 200$, $I_P = 1000$ and $E_P = 1000$)*

Above tables and simulations show that an increase in the values of minimum operation level ($\overline{q}_P$), peakload capacity (K_P) and start up cost (I_P) leads to an increase in both start up and shut down trigger levels. Furthermore, an increase in the shut down cost (E_P) increases the start up trigger but decreases the shut down trigger levels. These results further show that the monopolist's start up and shut down trigger price levels are higher than the social planner's. Therefore, compared to the social planner, the monopolist is expected to start up the peakload generator later and shut it down sooner. Hence, the monopolist is expected to keep the peakload generator active for a significantly shorter period of time.

5.3 Real Options Premium and Adjusted Learner Index

Analysis and determination of the extent of the market power in the electricity markets have been an important focus for the researchers. A detailed comparison of indices and models for detecting market power is given in Twomey *et al.* (2005). Vassilopoulos (2003) gives another rundown on these indices and models. Additionally, Wolfram (1999) derives estimates of price-cost mark-ups using direct measures of marginal cost and several approaches that do not rely on cost data, Wolak (2003) gives a measure for unilateral market power using Lerner Index, Newberry (2008) uses the Residual Supply Index approach to identify the ability of firms to raise prices, Wu *et al.* (2013) propose a long term market power measurement approach named *Transmission Constrained Network Flow*.

There are two main approaches to determine the extent of the market power of the firms: *ex-ante* and *ex-post* approaches. In this section, I focus on the *ex-post* determination of the extent of the market power of the monopolist using a price-cost mark-up approach. The main challenge behind price-cost mark-up approaches is considered to be the estimation of the marginal costs. However as denoted in the **Introduction**, due to the existence of the real options phenomena, the extent of the market power cannot be accurately determined by simply comparing the marginal cost to the market price even if the marginal cost is accurately estimated. Therefore compared to the existing literature, I give a more accurate *ex-post* measurement of market power by pinpointing the impact of uncertainty and certain operational characteristics on the start up and shut down decisions.

As I show in the numerical results below, both the monopolist and social planner wait for prices to rise above the marginal cost of their peakload generator prior starting up production. Due to market power, this result is standard for the case of the monopolist but not for the social planner. In other words, due to market uncertainty and operational characteristics of the power plants, even the social planner has to wait for the market price to be higher than its marginal cost prior to starting up the peakload generator (contrary to conventional $P = MC$ view). Therefore, we observe a mark-up for the social planner's case as if it is exercising market power. I refer to this *unavoidable* mark-up for the social planner as the *real options premium*.

By identifying *real options premium* in the social planner's case, we are now able to explain a part of the monopolist's mark-up during the periods where market power is exercised by withholding capacity. Considering **Figure 4**, the monopolist withholds capacity and does not start up the peakload generator when the demand shock level satisfies $X \in [X_H^{SP}, X_H^M)$. In this interval, the social planner produces electricity with the peakload generator whereas the monopolist does not. Therefore we start to see a market price difference between the cases of the social planner and the monopolist. Since the monopolist is to start up peakload generator when $X = X_H^M$, I consider the extent of the monopolist's ability to withhold capacity by comparing start up trigger prices of the social planner and the monopolist. Hence, the *real options adjusted* mark-up for the monopolist becomes a more accurate measure than the conventional Lerner Index for the extent of monopolist's ability to withhold capacity.

Table 3 and **Table 4** give mark-ups for the monopolist and social planner in the form of Price Cost Mark-up Index (*PCMI*). By definition, $PCMI$ for the social planner is simply the *real options premium.* In calculating *PCMI*, I take P_H^M and P_H^{SP} as the corresponding trigger prices prior to starting up the peakload generator for the monopolist and the social planner. The trigger prices and the *PCMI*'s are given as:

$$P_H^M = D[X_H^M, K_B] \text{ and } P_H^{SP} = D[X_H^{SP}, K_B] \tag{27}$$

$$PCMI^i = \frac{P_H^i - c_P}{c_P} \quad \text{for } i = M,\ SP. \tag{28}$$

Remark 6. *Since I am investigating the extent of market power (e.g., capacity withholding), I am primarily concerned with the monopolist's ability* *to increase prices prior to starting up the peakload generator. I do not use prices after start up because upon start up, there will be a downward jump in price (due to increased production) which will result in underestimating the extent of market power of the monopolist.*[8]

In the light of calculation of *real options premium*, I further compare the conventional Lerner Index (L_i) to the real options-adjusted Lerner Index ($\overline{L}_i$) for the monopolist. The aim is to give a better estimation for the market power. In that regard, for the calculation of $\overline{L}_i$, I put the social planner's start up trigger price instead of the marginal cost of peakload generator in the conventional formula of the Lerner Index. This way, I acknowledge the fact that even the social planner have to optimally start production at a price above the marginal cost. Therefore, definitions for conventional and real options-adjusted Lerner Indices for the monopolist are:

$$L_M = \frac{P_H^M - c_P}{P_H^M} \text{ and } \overline{L}_M = \frac{P_H^M - P_H^{SP}}{P_H^M}. \tag{29}$$

Sensitivity analysis in the following tables show significant levels of *real options premium* for both fixed and flexible peakload generation cases. Specifically, the *real options premium* takes values between 20%-55.4% of the marginal cost of the peakload generator for fixed peakload generation and between 4%-34.7% for flexible peakload generation. These levels of *real options premium* explain more than 24% of the monopolist's mark-up. So, ignoring *real options premium* results in significantly overestimating the market power of the monopolist. In that regard, real options-adjusted Lerner Index gives a better estimate of the extent of the monopolist's market power.

5.3.1 Fixed Peakload Generation Case

The table below shows how the real options premium in the fixed peakload generation case is affected by the capacity, start up cost and shut down cost of the peakload generator. An increase in all these three parameters increases the corresponding start up trigger prices and hence the value of the

[8]The same approach can also be applied to the regions where the monopolist shuts down peakload generator but the social planner keeps it operational, i.e. when $X \in (X_L^{SP}, X_L^M]$. In that case, *PCMI*'s can be calculated by comparing shut down prices of the monopolist and the social planner.

conventional Lerner Index. However, an increase in the start up trigger price does not necessarily increase the value of the real options-adjusted Lerner Index. **Table 3** shows that for some cases, the increase in the real options premium might be higher than the increase in the start up trigger price. So, a higher start up price does not necessarily indicate an increase in the extent of market power of the monopolist.

Table 3: *Real Options Premium for Fixed Peakload Generation*

K_P	I_P	E_P	P_H^M	P_H^{SP}	$PCMI^M$	$PCMI^{SP}$	L_M	$\overline{L}_M$
200	0	0	87.296	60.00	0.75	0.20	0.43	0.31
200	1000	0	119.626	67.389	1.40	0.35	0.58	0.43
200	1000	1000	121.999	69.181	1.44	0.38	0.59	0.43
400	1000	1000	140.318	77.731	1.80	0.55	0.64	0.45

5.3.2 Flexible Peakload Generation Case

The table below shows how the real options premium for flexible peakload generation case is affected by the minimum operation level, start up cost and shut down cost of the peakload generator. Contrary to the previous fixed peakload generation case, the capacity does not have an impact on the real options premium as the peakload generator is to be started at the mimum operation level. On the other hand, in line with the previous case, an increase in all these three parameters increases the corresponding start up trigger prices and the value of the conventional Lerner Index. **Table 4** shows that an increase in start up trigger price does not necessarily increase the value of the real options-adjusted Lerner Index.

Table 4: *Real Options Premium for Flexible Peakload Generation*

$\overline{q}_P$	I_P	E_P	P_H^M	P_H^{SP}	$PCMI^M$	$PCMI^{SP}$	L_M	$\overline{L}_M$
40	0	0	65.982	52.00	0.32	0.04	0.24	0.21
40	1000	0	109.905	64.595	1.20	0.29	0.54	0.41
40	1000	1000	113.395	67.222	1.27	0.34	0.56	0.41
80	1000	1000	113.53	67.383	1.27	0.35	0.56	0.41

5.4 Impact of Flexible Peakload Production

In this section, I investigate the impact of flexible peakload production on the start up trigger levels. In **Table 5** below, I give the difference between start up trigger price levels for fixed and flexible peakload generation cases. By nature, firms with fixed peakload production capabilities can only start up their production at full capacity. Therefore, the asking price to start up generation is expected to be higher for the fixed peakload production case. In other words, existence of peakload generators with fixed production could be expected to result in higher market clearing prices compared to flexible peakload production case. My aim in this section is to show the extent of the effect of fixed peakload generation on the start up trigger levels.

In the numerical analysis throughout **Section 5**, I do not consider the start up of the peakload generator at marginal quantitites to obtain more realistic results. Therefore, in **Table 5**, I investigate the case of a significantly high minimum operation level at 20% of the total peakload capacity. Specifically, I keep the base model parameters as before and fix the other key parameters at $K_P = 200$ and $\overline{q}_P = 40$.

Table 5: *Impact of Flexibility*

I_P	E_P	$\frac{P_H^M(Fixed) - P_H^M(Flexible)}{P_H^M(Fixed)}$	$\frac{P_H^{SP}(Fixed) - P_H^{SP}(Flexible)}{P_H^{SP}(Fixed)}$
0	0	0.244	0.133
1000	0	0.081	0.041
1000	1000	0.07	0.028

Under these conditions, **Table 5** shows that there is a significant impact of flexible peakload production on the start up trigger levels. Specifically, flexible peakload production helps to reduce the start up trigger levels. As mentioned previously, this result is rather intuitive as the monopolist (or the social planner) starts up production at higher quantities for the fixed peakload generation case. Furthermore, impact of flexible peakload production reduces with the start up and shut down costs. As a result, the difference between start up trigger levels go down from 24.4% to 7% for the monopoly case and from 13.3% to 2.8% for the social planner case.

6 Conclusion

This paper studies the effects of operational characteristics of power plants on optimal dispatch decisions and estimation of market power. Specifically, I provide a real options model to show how operational characteristics of power plants and market uncertainty affect the extent of *economic* capacity withholding. Furthermore, I derive start up and shut down trigger levels of the peakload generator for both monopoly and social planner cases. These trigger levels are obtained numerically due to the nature of the real options model. Numerical findings throughout this paper can be summarized as:

- An increase in the values of minimum operation level ($\overline{q}_P$), peakload capacity (K_P) and start up cost (I_P) leads to an increase in both start up and shut down trigger levels. Furthermore, an increase in the shut down cost (E_P) increases the start up trigger but decreases the shut down trigger levels.

- Due to higher start up and shut down trigger levels, the monopolist is expected to keep the peakload generator active for a significantly shorter period of time compared to the social planner.

- The social planner optimally waits for higher prices (than its marginal cost) prior to starting up the peakload generator. Comparing start up trigger prices for the social planner to marginal cost, reveals significant levels of *real options premium.* Under the existence of start up and shut down costs, the *real options premium* takes values of more than 30% of the marginal cost of the peakload generator.

- For both fixed and flexible peakload generation cases, the *real options premium* explains about 24% to 30% of the monopolist's mark-up.

- The real options-adjusted Lerner Index shows that an increase in start up trigger prices does not necessarily mean an increase in the extent of market power of the monopolist since the increase in *real options premium* may exceed the increase in start up trigger prices.

- Flexible peakload generation, compared to fixed peakload generation, helps to lower *real options premium* levels for the social planner and the extent of market power for the monopolist by lowering optimal start up trigger levels.

Overall, the existence of significant *real options premium* levels shows that ignoring market uncertainties and operational characteristics of individual generators, results in overestimating the extent of market power of the firms in the industry. Therefore, real options analysis can be an asset for more accurate investigations and decisions on the exercise of market power (e.g., economic capacity withholding). This result leads to a reinterpretation of the Lerner Index that takes the *real options premium* into account.

A Appendix Additional Model Details and Results

A.1 Monopolist production

A.1.1 System of Equations for Fixed Peakload Generation

$$A_1X_H^{\beta_1}+\frac{K_B}{r-\alpha}X_H-\frac{\gamma K_B^2}{r} = F_2X_H^{\beta_2}+\frac{K_B+K_P}{r-\alpha}X_H-\frac{\gamma(K_B+K_P)^2+c_PK_P}{r}-I_P \tag{30}$$

$$\beta_1A_1X_H^{\beta_1-1}+\frac{K_B}{r-\alpha} = \beta_2F_2X_H^{\beta_2-1}+\frac{K_B+K_P}{r-\alpha} \tag{31}$$

$$A_1X_L^{\beta_1}+\frac{K_B}{r-\alpha}X_L-\frac{\gamma K_B^2}{r}-E_P = F_2X_L^{\beta_2}+\frac{K_B+K_P}{r-\alpha}X_L-\frac{\gamma(K_B+K_P)^2+c_PK_P}{r} \tag{32}$$

$$\beta_1A_1X_L^{\beta_1-1}+\frac{K_B}{r-\alpha} = \beta_2F_2X_L^{\beta_2-1}+\frac{K_B+K_P}{r-\alpha} \tag{33}$$

Using above equations, in order to numerically solve for A_1, F_2, X_H and X_L, I derive the equations below:

$$(\beta_2-\beta_1)A_1X_H^{\beta_1} = \beta_2\left[\frac{\beta_2-1}{\beta_2}\frac{K_P}{r-\alpha}X_H-\frac{\gamma(2K_BK_P+K_P^2)+c_PK_P}{r}-I_P\right] \tag{34}$$

$$(\beta_1-\beta_2)F_2X_H^{\beta_2} = \beta_1\left[\frac{\beta_1-1}{\beta_1}\frac{K_P}{r-\alpha}X_H-\frac{\gamma(2K_BK_P+K_P^2)+c_PK_P}{r}-I_P\right] \tag{35}$$

$$(\beta_2-\beta_1)A_1X_L^{\beta_1}=\beta_2\left[\frac{\beta_2-1}{\beta_2}\frac{K_P}{r-\alpha}X_L-\frac{\gamma(2K_BK_P+K_P^2)+c_PK_P}{r}+E_P\right] \tag{36}$$

$$(\beta_1-\beta_2)F_2X_L^{\beta_2}=\beta_1\left[\frac{\beta_1-1}{\beta_1}\frac{K_P}{r-\alpha}X_L-\frac{\gamma(2K_BK_P+K_P^2)+c_PK_P}{r}+E_P\right] \tag{37}$$

A.1.2 System of Equations for Flexible Peakload Generation

$$\begin{aligned}A_1X_H^{\beta_1}+\frac{K_B}{r-\alpha}X_H-\frac{\gamma K_B^2}{r}=C_1X_H^{\beta_1}+C_2X_H^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}X_H\\-\frac{\gamma(K_B+\overline{q}_P)^2+c_P\overline{q}_P}{r}-I_P\end{aligned} \tag{38}$$

$$\beta_1A_1X_H^{\beta_1-1}+\frac{K_B}{r-\alpha}=\beta_1C_1X_H^{\beta_1-1}+\beta_2C_2X_H^{\beta_2-1}+\frac{K_B+\overline{q}_P}{r-\alpha} \tag{39}$$

$$\begin{aligned}A_1X_L^{\beta_1}+\frac{K_B}{r-\alpha}X_L-\frac{\gamma K_B^2}{r}-E_P=C_1X_L^{\beta_1}+C_2X_L^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}X_L\\-\frac{\gamma(K_B+\overline{q}_P)^2+c_P\overline{q}_P}{r}\end{aligned} \tag{40}$$

$$\beta_1A_1X_L^{\beta_1-1}+\frac{K_B}{r-\alpha}=\beta_1C_1X_L^{\beta_1-1}+\beta_2C_2X_L^{\beta_2-1}+\frac{K_B+\overline{q}_P}{r-\alpha} \tag{41}$$

$$\begin{aligned}C_1\underline{X}^{\beta_1}\quad+\quad C_2\underline{X}^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}\underline{X}-\frac{\gamma(K_B+\overline{q}_P)^2+c_P\overline{q}_P}{r}=\\D_1\underline{X}^{\beta_1}\quad+\quad D_2\underline{X}^{\beta_2}+\frac{1}{4\gamma}\left[\frac{\underline{X}^2}{r-2\alpha-\sigma^2}-\frac{2c_P}{r-\alpha}\underline{X}+\frac{c_P^2}{r}\right]+\frac{c_PK_B}{r}\end{aligned} \tag{42}$$

$$\begin{aligned}\beta_1C_1\underline{X}^{\beta_1-1}+\beta_2C_2\underline{X}^{\beta_2-1}+\frac{K_B+\overline{q}_P}{r-\alpha}=\beta_1D_1\underline{X}^{\beta_1-1}+\beta_2D_2\underline{X}^{\beta_2-1}\\+\frac{1}{4\gamma}\left[\frac{2\underline{X}}{r-2\alpha-\sigma^2}-\frac{2c_P}{r-\alpha}\right]\end{aligned} \tag{43}$$

$$D_1\overline{X}^{\beta_1} + D_2\overline{X}^{\beta_2} + \frac{1}{4\gamma}\left[\frac{\overline{X}^2}{r-2\alpha-\sigma^2} - \frac{2c_P}{r-\alpha}\overline{X} + \frac{c_P^2}{r}\right] + \frac{c_P K_B}{r} =$$

$$F_2\overline{X}^{\beta_2} + \frac{K_B+K_P}{r-\alpha}\overline{X} - \frac{\gamma(K_B+K_P)^2 + c_P K_P}{r} \quad (44)$$

$$\beta_1 D_1\overline{X}^{\beta_1-1} + \beta_2 D_2\overline{X}^{\beta_2-1} + \frac{1}{4\gamma}\left[\frac{2\overline{X}}{r-2\alpha-\sigma^2} - \frac{2c_P}{r-\alpha}\right] = \beta_2 F_2\overline{X}^{\beta_2-1} + \frac{K_B+K_P}{r-\alpha} \quad (45)$$

where $\beta_1 > 1$, $\beta_2 < 0$, $\overline{X} = [2\gamma(K_B+K_P)+c_P]$ and $\underline{X} = [2\gamma(K_B+\overline{q}_P)+c_P]$. Furthermore, β_1, β_2 are solutions for the following quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \quad (46)$$

Given the value-matching and smooth-pasting conditions, analytical solutions for C_1, $C_2 - D_2$, D_1 and $D_2 - F_2$ exist. However, analytical solutions for $A1$, $C2$, X_H and X_L do not exist. Hence, I conduct numerical analysis by using the equations (38) - (41). I provide the numerical solutions in Section 5.

A.2 Social planner's production

A.2.1 System of Equations for Fixed Peakload Generation

$$G_1X_H^{\beta_1} + \frac{K_B}{r-\alpha}X_H - \frac{\gamma K_B^2}{2r} = N_2X_H^{\beta_2} + \frac{K_B+K_P}{r-\alpha}X_H - \frac{\gamma(K_B+K_P)^2 + 2c_PK_P}{2r} - I_P \quad (47)$$

$$\beta_1G_1X_H^{\beta_1-1} + \frac{K_B}{r-\alpha} = \beta_2N_2X_H^{\beta_2-1} + \frac{K_B+K_P}{r-\alpha} \quad (48)$$

$$G_1X_L^{\beta_1} + \frac{K_B}{r-\alpha}X_L - \frac{\gamma K_B^2}{2r} - E_P = N_2X_L^{\beta_2} + \frac{K_B+K_P}{r-\alpha}X_L - \frac{\gamma(K_B+K_P)^2 + 2c_PK_P}{2r} \quad (49)$$

$$\beta_1G_1X_L^{\beta_1-1} + \frac{K_B}{r-\alpha} = \beta_2N_2X_L^{\beta_2-1} + \frac{K_B+K_P}{r-\alpha} \quad (50)$$

Using above equations, in order to numerically solve for A_1, F_2, X_H and X_L, I derive the equations below:

$$(\beta_2-\beta_1)G_1X_H^{\beta_1}=\beta_2\left[\frac{\beta_2-1}{\beta_2}\frac{K_P}{r-\alpha}X_H-\frac{\gamma(2K_BK_P+K_P^2)+2c_PK_P}{2r}-I_P\right] \tag{51}$$

$$(\beta_1-\beta_2)N_2X_H^{\beta_2}=\beta_1\left[\frac{\beta_1-1}{\beta_1}\frac{K_P}{r-\alpha}X_H-\frac{\gamma(2K_BK_P+K_P^2)+2c_PK_P}{2r}-I_P\right] \tag{52}$$

$$(\beta_2-\beta_1)G_1X_L^{\beta_1}=\beta_2\left[\frac{\beta_2-1}{\beta_2}\frac{K_P}{r-\alpha}X_L-\frac{\gamma(2K_BK_P+K_P^2)+2c_PK_P}{2r}+E_P\right] \tag{53}$$

$$(\beta_1-\beta_2)N_2X_L^{\beta_2}=\beta_1\left[\frac{\beta_1-1}{\beta_1}\frac{K_P}{r-\alpha}X_L-\frac{\gamma(2K_BK_P+K_P^2)+2c_PK_P}{2r}+E_P\right] \tag{54}$$

A.2.2 System of Equations for Flexible Peakload Generation

$$\begin{aligned}G_1X_H^{\beta_1}+\frac{K_B}{r-\alpha}X_H-\frac{\gamma K_B^2}{2r}=J_1X_H^{\beta_1}+C_2X_H^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}X_H\\-\frac{\gamma(K_B+\overline{q}_P)^2+2c_P\overline{q}_P}{2r}-I_P\end{aligned} \tag{55}$$

$$\beta_1G_1X_H^{\beta_1-1}+\frac{K_B}{r-\alpha}=\beta_1J_1X_H^{\beta_1-1}+\beta_2C_2X_H^{\beta_2-1}+\frac{K_B+\overline{q}_P}{r-\alpha} \tag{56}$$

$$\begin{aligned}G_1X_L^{\beta_1}+\frac{K_B}{r-\alpha}X_L-\frac{\gamma K_B^2}{2r}-E_P=J_1X_L^{\beta_1}+J_2X_L^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}X_L\\-\frac{\gamma(K_B+\overline{q}_P)^2+2c_P\overline{q}_P}{2r}\end{aligned} \tag{57}$$

$$\beta_1G_1X_L^{\beta_1-1}+\frac{K_B}{r-\alpha}=\beta_1J_1X_L^{\beta_1-1}+\beta_2J_2X_L^{\beta_2-1}+\frac{K_B+\overline{q}_P}{r-\alpha} \tag{58}$$

$$\begin{aligned}J_1\underline{X}^{\beta_1}\ &+\ J_2\underline{X}^{\beta_2}+\frac{K_B+\overline{q}_P}{r-\alpha}\underline{X}-\frac{\gamma(K_B+\overline{q}_P)^2+2c_P\overline{q}_P}{2r}=\\M_1\underline{X}^{\beta_1}\ &+\ M_2\underline{X}^{\beta_2}+\frac{1}{2\gamma}\left[\frac{\underline{X}^2}{r-2\alpha-\sigma^2}-\frac{2c_P}{r-\alpha}\underline{X}+\frac{c_P^2}{r}\right]+\frac{c_PK_B}{r}\end{aligned} \tag{59}$$

$$\beta_1 J_1 \underline{X}^{\beta_1 - 1} + \beta_2 J_2 \underline{X}^{\beta_2 - 1} + \frac{K_B + \overline{q}_P}{r - \alpha} = \beta_1 M_1 \underline{X}^{\beta_1 - 1} + \beta_2 M_2 \underline{X}^{\beta_2 - 1} + \frac{1}{2\gamma}\left[\frac{2\underline{X}}{r - 2\alpha - \sigma^2} - \frac{2c_P}{r - \alpha}\right] \quad (60)$$

$$M_1 \overline{X}^{\beta_1} + M_2 \overline{X}^{\beta_2} + \frac{1}{2\gamma}\left[\frac{\overline{X}^2}{r - 2\alpha - \sigma^2} - \frac{2c_P}{r - \alpha}\overline{X} + \frac{c_P^2}{r}\right] + \frac{c_P K_B}{r} = N_2 \overline{X}^{\beta_2} + \frac{K_B + K_P}{r - \alpha}\overline{X} - \frac{\gamma (K_B + K_P)^2 + 2 c_P K_P}{2r} \quad (61)$$

$$\beta_1 M_1 \overline{X}^{\beta_1 - 1} + \beta_2 M_2 \overline{X}^{\beta_2 - 1} + \frac{1}{2\gamma}\left[\frac{2\overline{X}}{r - 2\alpha - \sigma^2} - \frac{2c_P}{r - \alpha}\right] = \beta_2 N_2 \overline{X}^{\beta_2 - 1} + \frac{K_B + K_P}{r - \alpha} \quad (62)$$

where $\beta_1 > 1$, $\beta_2 < 0$, $\overline{X} = [\gamma(K_B + K_P) + c_P]$ and $\underline{X} = [\gamma(K_B + \overline{q}_P) + c_P]$. Furthermore, β_1, β_2 are solutions for the following quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \quad (63)$$

Given the value-matching and smooth-pasting conditions, analytical solutions for J_1, $J_2 - M_2$, M_1 and $M_2 - N_2$ exist. However, analytical solutions for G_1, J_2, X_H and X_L do not exist. Hence, I conduct numerical analysis by using the equations (55) - (58). I provide the numerical solutions in **Section 5**.

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Wind Generators and Market Power: Does it matter who owns them?

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Abstract

Electricity production from wind power generators holds significant importance in European Union's 20% renewable energy target by 2020. In this paper, using a Cournot oligopoly model, I investigate the short term effects of wind generator ownership by owners of fossil-fueled peakload generators. I show that aggregate wind generator ownership reduces the positive impact of the wind generation on the market outcomes and as a result the total peakload production decreases and the market price increases. Furthermore, when all wind generators are owned by the peakload firms, the impact of wind generation on the market outcomes vanishes. Additionally, start up and shut down (suspension) price thresholds are significantly higher when the owner of peakload capacity also owns a share of wind power generators. I also find that a *feed-in premium* support scheme does not affect the peakload firms production levels and hence the market outcomes. However, under a *feed-in tariff* type of support scheme, there is an increase in the total production and a decrease in the market price.

Keywords: Oligopoly, electricity, wind.

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1 Introduction and Literature Review

Electricity production from wind power generators holds significant importance in European Union's 20% renewable energy target by 2020. On the upside, wind power is considered to be a low-cost, environmentally friendly and non-strategic way to produce electricity. On the downside, wind power production is stochastic and it may require high levels of operating reserves to maintain a certain level of security of supply.

In this paper, using a Cournot oligopoly model, I investigate the short term effects of wind generator ownership by owners of fossil-fueled peakload generators. I show that aggregate wind generator ownership reduces the positive impact of the wind generation on the market outcomes and as a result the total peakload production decreases and the market price increases. Furthermore, when all wind generators are owned by the peakload firms, the impact of wind generation on the market outcomes vanishes. Additionally, start up and shut down (suspension) price thresholds are significantly higher when the owner of peakload capacity also owns a share of wind power generators. I also find that a *feed-in premium* support scheme does not affect the peakload firms production levels and hence the market outcomes. However, under a *feed-in tariff* type of support scheme, there is an increase in the total production and a decrease in the market price.

A number of papers focus on the short and long term impacts of high levels of wind/renewable power penetration in liberalized electricity markets. Sensfuß *et al.* (2008) analyze the impact of renewable electricity generation on the electricity market in Germany. Lamont (2008) investigates the system-wide effects of large-scale intermittent technologies in an electric generation system. Green and Vasilakos (2009) evaluate the impact of intermittent wind generation on hourly equilibrium prices and output. Bushnell (2010) models the impact of large amount of wind generation on the generation mix. Twomey and Neuhoff (2010) investigate how the relationship between wind production and market price is affected by market power. Ketterer (2012) investigates the price volatility effects of intermittent wind power generation in Germany. Ambec and Crampes (2012) analyze the basic parameters that should be considered to determine the capacity of intermittent and non-intermittent production plants anticipating their efficient dispatch. Bouckaert and De Borger (2013) study strategic capacity choices between conventional dispatchable and intermittent generation technologies.

In the relevant literature (Sensfuß *et al.* (2008), Green and Vasilakos (2009), Twomey and Neuhoff (2010)), wind production is simply regarded as a negative shock to demand and it lowers the need for electricity from conventional, fossil-fueled generators. However, this perspective greatly ignores the effects of ownership of wind generators. Those effects are important because ownership of the wind generators creates additional rents for the firms that exercise market power with their conventional generators. Therefore we may expect firms, that have wind generators in their generation portfolio, to produce less electricity with their conventional generators than those who do not own any wind generators at all. As a result, we may further expect different market outcomes for different ownership structures given the same level of wind production.

This paper can be regarded as an extension of Twomey and Neuhoff (2010). For the Cournot model, I keep their basic model structure and extend their findings by introducing different market competition scenarios based on the ownership of wind generators. They focus on the competition at the conventional generator level and disregard the possibility of the ownership of wind generators by the existing conventional generator owners. On the other hand, I calculate the equilibrium production levels and market prices to see the effects of different ownership scenarios of the wind generators.

The rest of the paper is organized as follows: In section 2, I set up a Cournot oligopoly model and provide an analysis on the equilibrium production levels to investigate the effects of wind generator ownership on the market outcomes as well as start up and shut down decisions. In section 3, I give a discussion on the impact of the internalization of wind generation from a welfare point of view. In section 4, I investigate the effects of two main types of renewable support schemes on the market outcomes. In section 5, I give a brief conclusion on my findings.

2 The Model

In the short term, there are two ways to exercise market power for (peakload) firms in the electricity markets. First, firms can decrease the level of output by withholding capacity (Joskow and Kahn, 2002). Second, they expectedly operate their generators for a significantly shorter period of time by asking higher start up and shut down prices than the corresponding socially optimal case (Misir, 2014). Furthermore Green and Vasilakos (2009) note that a strategic generator that owns wind farms would wish to take their wind output into account when calculating the supply function from its thermal plants. In this section, following the argument of Green and Vasilakos (2009) and adopting the basic model set up of Twomey and Neuhoff (2010), I provide a Cournot oligopoly model that incorporates different wind generator ownership scenarios under oligopolistic peakload competition. I aim to show how optimal capacity withholding and dispatch decisions of the peakload firms are affected by wind generator ownership.

In this section, I assume that the industry consists of two types of electricity generation technologies: *wind* (W) and conventional *peakload* (P) generation. I do not put restrictions on the number of generators available for each technology as I assume that peakload generators could be instantly started up and shut down without any costs. I further assume that wind generation is subject to exogenous shocks and zero marginal cost of production, whereas peakload generation has constant marginal cost of production $c > 0$.

At time t, the industry output is determined by the sum of wind and peakload production: $Q(t) = Q_W(t) + Q_P(t)$. Instantaneous stochastic wind production is given by:

$$Q_W(t) = Q_{W,0} + \epsilon_t \geq 0 \tag{1}$$

where $Q_{W,0}$ is the average wind production level, ϵ_t is the exogenous shock to the wind production with the support $[-Q_{W,0}, \infty)$ and properties $E[\epsilon_t] = 0$ and $Var[\epsilon_t] = \sigma^2$.

There are no side payments and regardless of the technology, all production is paid the market clearing price. The market price fluctuates stochastically according to linear inverse demand function, $D : \mathbb{R}_+ \to \mathbb{R}$:

$$P(t) = D[Q_P(t) + Q_W(t)] = X - \gamma Q(t) \ \ \text{with } \gamma > 0. \tag{2}$$

where $X > c$ is the constant demand intercept.

Below, I describe two different market scenarios. First, I investigate the benchmark case where there is a social planner or perfect competition in the industry. Second, I investigate the case where there is oligopolistic Cournot competition at the peakload level. For the oligopolistic competition, I give the results of wind generator ownership on total production and market price. I further provide results on welfare implications as well as start up and shut down decisions of peakload generators.

2.1 Social Planning and Competitive Equilibrium

I set the benchmark by calculating the optimal production and market price in the case of the social planner. The social planner's objective is to maximize total social surplus by deciding how much to produce by conventional peakload generators given the level of wind production. In order to maximize total social surplus, $S[Q^{SP}(t)]$, the social planner will have to calculate the area under the demand curve for a given production level and subtract total cost of production, $C[Q^{SP}(t)]$. As $Q^{SP}(t) = Q_P(t) + Q_W(t)$, we have:

$$\begin{aligned} S[Q^{SP^*}(t)] &= sup_{Q_P}\left\{\left[\int_0^{Q^{SP}(t)}(X-\gamma q)dq\right] - C[Q^{SP}(t)]\right\} \\ &= sup_{Q_P}\left\{X(Q_P+Q_W(t)) - \frac{\gamma(Q_P+Q_W(t))^2}{2} - cQ_P\right\} \quad (3) \end{aligned}$$

The first order condition entails:

$$Q_P(t) = \frac{X-c}{\gamma} - Q_W(t) \Longrightarrow Q^{SP}(t) = \frac{X-c}{\gamma} \Longrightarrow P^{SP}(t) = c. \quad (4)$$

It follows from **(4)** that the social planner fully internalizes the effects of wind generation and as a result, the total socially optimal level of production does not depend on total wind production. But if total wind production is higher than the total socially optimal level of production (i.e., $Q_W(t) > (X-c)/\gamma$), there will be no production coming from the peakload generators and the market price will be even lower than the marginal cost of peakload generation. On the other hand, for the case of perfect competition at the peakload level, one should start with the very last step in **(4)**. Since, perfectly competitive firms are price takers and equate price to marginal cost to find out how much to produce, the market outcome for the cases of social planner and perfect competition will be the same.

Remark 1. *Ownership structures of the wind generators do not have an impact on the aggregate peakload production and market price for the case of perfect competition at the peakload level. Perfectly competitive peakload firms observe the total wind production and decide how much to produce at the peakload level in order to reach the equilibrium production and price levels given in (4). In other words, perfectly competitive peakload firms produce enough to set the market price to marginal cost. Therefore, we end up with the same market outcome regardless of the structure of the wind generator ownership.*

2.2 Oligopolistic Cournot Competition

In this section, I investigate the market outcomes under the existence of oligopoly at the peakload level. I derive a general formula for the equilibrium peakload generation levels depending on the ownership of wind generators. I aim to show how wind generator ownership affects the individual firms' production levels and the industry outcomes. The results in this section show that all the peakload firms are influenced by the aggregate wind generator ownership regardless of their individual ownership status.

There are n symmetric firms at the peakload level with the same constant marginal cost of peakload production, $c > 0$. I assume that $k \leq n$ firms equally own a share of wind generators and the rest of the firms at the peakload level do not own any wind generators at all. By assuming uniform production throughout wind generators, I consider that ownership of an equal share of wind generators results in an equal share of wind power production for each firm. Without loss of generality, for any firm $j \in J = \{k+1, k+2, ..., n\}$ who does not own any wind generators, the total production is just the individual peakload production, $Q_{P,j}(t)$. Consequently, for any firm $i \in I = \{1, 2, ..., k\}$ who owns an equal share of wind generators, the total individual production is the sum of peakload production and the share of total wind production.[1] Namely;

$$Q_i(t) = Q_{P,i}(t) + \mathbf{A}Q_W(t) \tag{5}$$

$\mathbf{A} \in \mathbb{Q}$ is a rational number denoting the share of total wind generators owned by each of the k peakload firms. This share is formally defined by:

$$\mathbf{A} := \frac{\alpha}{k} \tag{6}$$

where $\alpha \in [0, 1]$ is the share of wind generators aggregately owned by the peakload firms. Specifically, $\alpha = 0$ when the peakload firms do not own any of the wind generators and $\alpha = 1$ when the peakload firms own all of the wind generators.

Given this model, there are two types of profit functions depending on a firm's wind generator ownership status. For any firm $i \in I$, with wind generator ownership, the profit function is:

$$\Pi_i(t) = [X - \gamma(Q_{P,i} + Q_{P,i'} + Q_{P,n-k} + Q_W(t))](Q_{P,i} + \mathbf{A}Q_W(t)) - cQ_{P,i} \tag{7}$$

where $Q_{P,i'}$ is the aggregate peakload production of the firms with wind generator ownership except for firm i and $Q_{P,n-k}$ is the aggregate peakload production of the firms without wind generator ownership.

Similarly for any firm $j \in J$, without wind generator ownership, the profit function is:

$$\Pi_j(t) = [X - \gamma(Q_{P,j} + Q_{P,j'} + Q_{P,k} + Q_W(t))]Q_{P,j} - cQ_{P,j} \tag{8}$$

where $Q_{P,j'}$ is the aggregate peakload production of the firms without wind generator ownership except for firm j and $Q_{P,k}$ is the aggregate peakload production of the firms with wind generator ownership.

Given the above profit functions, first order conditions entail (see **Appendix A.1**) the following equilibrium peakload production levels for firms i and j:

$$Q^*_{P,j}(t) = \frac{X - c}{\gamma(n+1)} - \frac{1-\alpha}{n+1}Q_W(t) \tag{9}$$

[1]Although it turns out that my model setup is very close to another recent paper Ben-Moshe and Rubin (2014), my model allows for asymmetric ownership of the wind generators. Therefore, it potentially provides more generalized and realistic results.

$$Q^*_{P,i}(t) = \frac{X-c}{\gamma(n+1)} - \frac{1-\alpha}{n+1}Q_W(t) - \mathbf{A}Q_W(t) = Q^*_{P,j}(t) - \mathbf{A}Q_W(t) \quad (10)$$

Looking at **(9)**, we see two different terms. The first term is the symmetric equilibrium level of individual production if the industry did not have any wind generators at all. The second term is the negative effect of unowned/un-internalized wind generation on the peakload production. The effect is as if there is a non-strategic firm that just produces $(1-\alpha)Q_W(t)$ amount of electricity.

On the other hand, looking at **(10)**, there is an additional term ($\mathbf{A}Q_W(t)$) in firm i's equilibrium peakload production. This term is the level of internalized wind generation for the peakload firms with wind generator ownership. The internalization results in a decrease in the level of individual peakload production exactly by the amount of the individual share of wind generation. Therefore, total (wind plus peakload) production for each peakload firm is the same but wind generator ownership results in higher profits as total cost of production goes down due to zero-cost wind generation.

Proposition 2. *For any peakload firm with wind generator ownership, peakload production decreases with the level of wind production and aggregate wind generator ownership, whereas it increases with the total number of peakload firms with wind generator ownership when there is positive wind generation in the market.*

i.e., for any firm $i \in I$*, we have* $\partial Q_{P,i}/\partial \epsilon_t < 0$*,* $\partial Q_{P,i}/\partial \alpha < 0$ *and* $\partial Q_{P,i}/\partial k > 0$ *for* $Q_W(t) > 0$*.*

Proof. From **(10)** we have;

$$\frac{\partial Q_{P,i}}{\partial \epsilon_t} = -\frac{1-\alpha}{n+1} - \frac{\alpha}{k} < 0 \quad (11)$$

$$\frac{\partial Q_{P,i}}{\partial \alpha} = \left(\frac{1}{n+1} - \frac{1}{k}\right)(Q_{W,0} + \epsilon_t) < 0 \quad (12)$$

$$\frac{\partial Q_{P,i}}{\partial k} = \frac{\alpha}{k^2}(Q_{W,0} + \epsilon_t) > 0 \quad (13)$$

□

Proposition 3. *For any peakload firm with no wind generator ownership, peakload production decreases with the level of wind production and increases* *with the aggregate wind generator ownership, whereas it does not change with the total number of peakload firms with wind generator ownership when there is positive wind generation in the market.*

i.e., for any firm $j \in J$, *we have* $\partial Q_{P,j}/\partial \epsilon_t < 0$, $\partial Q_{P,j}/\partial \alpha > 0$ *and* $\partial Q_{P,j}/\partial k = 0$ *for* $Q_W(t) > 0$.

Proof. From **(9)** we have;

$$\frac{\partial Q_{P,j}}{\partial \epsilon_t} = -\frac{1-\alpha}{n+1} < 0 \tag{14}$$

$$\frac{\partial Q_{P,j}}{\partial \alpha} = \frac{1}{n+1}(Q_{W,0} + \epsilon_t) > 0 \tag{15}$$

$$\frac{\partial Q_{P,j}}{\partial k} = 0 \tag{16}$$

□

Proposition 2 and **Proposition 3** show that wind generation decreases the individual peakload production levels for all peakload firms. However, for positive values of α, this effect is dampened and all peakload firms increase their total production levels. In other words, even if a peakload firm does not own any wind generators, it still benefits from the aggregate wind generator ownership knowing that its competitors are decreasing their peakload productions. Specifically, if a peakload firm owns a share of the wind generators, it decreases its peakload production exactly by the amount of its share of wind generation. As a result, the overall effect of aggregate wind generator ownership on the peakload production is negative for the firms with wind generator ownership since they provide a fraction of their production from zero-cost wind generation.

Lemma 4. *If the number of symmetric firms that collectively own* α *share of wind generators changes, the total peakload production stays the same.*

Proof. In order to prove the lemma, it is sufficient to show that the total peakload production for the symmetric equilibrium does not depend on the parameter k.

So, taking the previously derived expressions for $Q_{P,i}$ and $Q_{P,j}$ into account, the total peakload production is:

$$Q_P(t) = kQ_{P,i}(t) + (n-k)Q_{P,j}(t) = \frac{n}{n+1}\frac{X-c}{\gamma} - \frac{n+\alpha}{n+1}Q_W(t) \qquad (17)$$

which does not depend on k. □

Proposition 5. *Following* **(17)***, total production and market price are given by:*

$$Q(t) = \frac{n}{n+1}\frac{X-c}{\gamma} + \frac{1-\alpha}{n+1}Q_W(t) \quad \text{and} \quad P(t) = \frac{X+nc}{n+1} - \frac{\gamma(1-\alpha)}{n+1}Q_W(t) \qquad (18)$$

The market price (total production) decreases (increases) with the level of wind production and increases (decreases) with the aggregate wind generator ownership when there is positive wind generation in the market. In other words, aggregate wind generation ownership reduces the positive impact of the wind generation on the market outcomes and as a result it increases the market power of the peakload firms.

Proof. It follows from **(18)** that:

$$\frac{\partial P}{\partial \epsilon_t} = -\frac{\gamma(1-\alpha)}{n+1} < 0 \qquad (19)$$

$$\frac{\partial Q}{\partial \epsilon_t} = \frac{1-\alpha}{n+1} > 0 \qquad (20)$$

$$\frac{\partial P}{\partial \alpha} = \frac{\gamma}{n+1}(Q_{W,0} + \epsilon_t) > 0 \qquad (21)$$

$$\frac{\partial Q}{\partial \alpha} = -\frac{Q_{W,0} + \epsilon_t}{n+1} < 0 \qquad (22)$$

□

It follows from **(9)** and **(10)** that when $\alpha = 1$, total peakload production decreases exactly by the amount of the total wind production and as a result, total industry production and the market price do not depend on the level of wind production. This is simply because, when all of the wind generators are owned by the peakload firms, the effects of wind generation are entirely internalized by the peakload firms. Furthermore, as $0 < \alpha < 1$, $\partial P/\partial\alpha > 0$. In other words, if the aggregate ownership of the wind generators by the peakload firms increases, so does the market price.

Following **(18)**, **Figure 1** depicts the effect of aggregate wind generator ownership on the residual demand curve that peakload firms face. As I pointed out in **Section 1**, if we disregard wind generator ownership of the peakload firms, wind generation is expected to decrease the demand exactly by its current level. But as I showed in **(10)**, peakload firms internalize their share of wind production in equilibrium. Hence, the residual demand that the peakload firms face will be subject to the level of aggregate wind generator ownership.

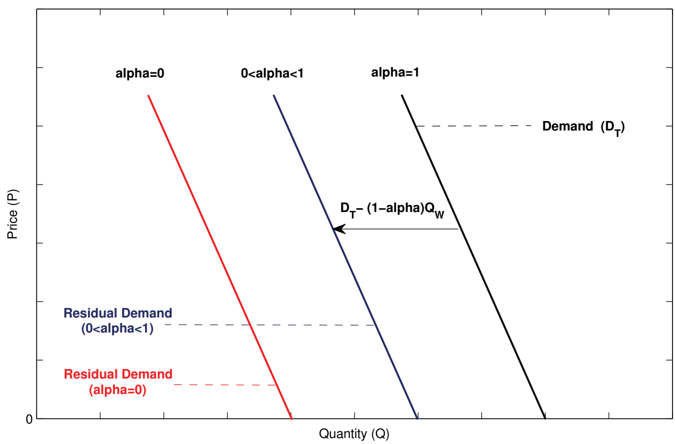

Figure 1: *Effect of aggregate wind generator ownership (α) on the residual demand curve.*

Looking at **Figure 1**, we see that when $\alpha = 0$, none of the wind generators are owned by the peakload firms and the demand curve shifts to the left exactly by the amount of the current level of wind generation. On the other hand, when $0 < \alpha < 1$, the residual demand curve shifts closer back to the original demand due to internalization of the wind production. In other words, total demand does only decrease by the level of uninternalized wind generation ($(1-\alpha)Q_W(t)$). Moreover, when $\alpha = 1$, the effect of uninternalized wind generation vanishes and as a result, the residual demand and original demand curves coincide.

In summary, wind generator ownership provides a higher level of market power to the peakload firms and as a result, the total production and the market price increases with aggregate wind power ownership (α). Additionally, it can be seen from **(18)** that, as the number of peakload firms approaches infinity, the increase in market power resulting from owning wind generators becomes infinitesimal. Hence, the effects of aggregate wind generator ownership vanishes.

2.3 Start up and Shut down Decisions

In **Section 2.2**, I calculated the equilibrium peakload production levels depending on the status of wind generator ownership. Given the model structure, the peakload firms first observe the level of wind generation. Afterwards, when the level of wind generation is high enough, the peakload generators are shut down and when the wind generation is low enough, the peakload generators are started up.[2] Since it is not possible to have negative peakload generation, equilibrium peakload production levels given in **(9)** and **(10)** must be non-negative. As there are no start up or shut down costs in the model, there will be a single wind generation threshold for both start up and shut down decisions of a specific firm to satisfy the non-negativity constraint of peakload production.[3]

In this section, I provide a basic analysis on the start up and shut down decisions of the peakload generators by calculating the (start up/shut down wind generation) threshold for the firms with wind generator ownership, $\overline{Q}_i$, and the threshold for the firms without wind generator ownership, $\overline{Q}_j$.

Looking at the corresponding equilibrium peakload production levels in **(9)** and **(10)**, the thresholds are different for the firms with and without wind generator ownership. When $\alpha = 0$, all peakload firms have the same threshold. As $0 < \alpha < 1$, by equating the corresponding equilibrium peakload production level to zero for any firm i that owns $\mathbf{A}$ share of total wind generators, the threshold is given by:

$$\overline{Q}_i = \frac{1}{1 - \alpha + \mathbf{A}(n+1)} \frac{X - c}{\gamma} \tag{23}$$

For any firm j that does not own any wind generators, the threshold is given by:

$$\overline{Q}_j = \frac{1}{1 - \alpha} \frac{X - c}{\gamma} \tag{24}$$

We see that $\mathbf{A}(n+1) > 0$ since $\alpha > 0$. Then, it follows from **(23)** and **(24)**

[2] In this context, *start up* means positive peakload generation whereas *shut down* means zero peakload generation.

[3] If there exists start up and/or shut down costs for the peakload generators, the start up thresholds would be higher than the shut down thresholds for the peakload firms (see Misir (2014)).

that $\overline{Q}_i < \overline{Q}_j$. In other words, peakload firms that own wind generators will decide not to produce with their peakload generators for lower realizations of total wind generation, $Q_W(t)$. In other words, wind generator ownership results in peakload generators to start up or shut down production at a lower wind generation level. If we think in terms of prices, due to downward sloping demand curve, corresponding price thresholds become higher for the peakload firms with wind generator ownership. As a result, wind generator ownership increases the price thresholds as it increases the market power of the peakload firms. We further see that $\partial\overline{Q}_i/\partial\alpha < 0$ and $\partial\overline{Q}_j/\partial\alpha > 0$. In other words, as the aggregate ownership of wind generators (α) increases, there are opposite impacts on the thresholds. Hence, the difference between thresholds for firm i and j increases.

In summary, increased market power of a peakload firm due to wind generator ownership, allows it to start up its peakload generator later and shut it down earlier compared to the firms with no wind generator ownership. This result happens because the increased market price will positively affect the profits coming from the wind generators for the firms with wind generator ownership. It is clear that the model in this paper neither adopts a continuous-time (Misir (2014)) nor a discrete-time (see Dixit and Pindyck (1994)) setup that could help us to fully investigate the impact of wind generation ownership on the start up and shut down decisions. In such models, it can be expected to see the difference between start up and shut down thresholds to get even bigger with the introduction of an intertemporal model allowing start up and shut down costs.

3 Welfare Implications

As it was mentioned before, when wind generation is high enough, there will not be any need for peakload generation. Therefore, peakload firms will not have any strategic actions to take when facing sufficiently large wind generation levels. As a result, aggregate wind generator ownership does not have an impact on consumer and producer surplus when peakload generators are idle. In this section, the derivations apply to the situation in which wind generation is so low that all the firms in the industry find it profitable to produce electricity with their peakload generators.

For that situation, I provide the effects of wind generator ownership on producer surplus, consumer surplus and total social surplus for the models given in the previous section. I specifically focus on the relationship between aggregate wind generator ownership and the volatility of wind generation. The derivations below show that aggregate wind generator ownership does not have an impact for the case of social planner. However, derivations show that aggregate wind generator ownership reduces the effects of volatility of the wind generation for the oligopoly case because of the internalization of wind generation.

3.1 Social Planner

As stated in **Remark 1**, ownership structures of the wind generators do not have an effect on the socially optimal level of production. Using the conventional definitions (see **3.2**), expressions for consumer surplus as well as producer surplus and total social surplus for the case of social planner (or perfect competition) are:

$$CS^{SP} = \frac{(X-c)^2}{2\gamma} \;\;, PS^{SP} = c(Q_{W,0} + \epsilon_t) \;\;, S^{SP} = \frac{(X-c)^2}{2\gamma} + c(Q_{W,0} + \epsilon_t) \tag{25}$$

Therefore, expected values are given by

$$E[CS^{SP}] = \frac{(X-c)^2}{2\gamma} \;\;, E[PS^{SP}] = cQ_{W,0} \;\;, E[S^{SP}] = \frac{(X-c)^2}{2\gamma} + cQ_{W,0} \tag{26}$$

Due to internalization of the entire wind generation; $E[CS^{SP}]$, $E[PS^{SP}]$ and $E[S^{SP}]$ do not depend on the volatility, σ^2. Furthermore, $\partial CS^{SP}/\partial\epsilon_t = 0$, $\partial PS^{SP}/\partial\epsilon_t > 0$ and $\partial S^{SP}/\partial\epsilon_t > 0$. In other words, producer surplus and total social surplus increase with wind production whereas consumer surplus does not change. This result is obtained since producer surplus is simply the cost savings due to internalized wind generation. Therefore, producer surplus and hence total social surplus are positively affected by the level of wind generation.

3.2 Cournot Oligopoly

In this section, I investigate the effects of wind generator ownership on the (expected) consumer surplus, producer surplus and total social surplus for the oligopoly case. By using the conventional definitions, I derive expected consumer surplus ($E[CS^{\alpha}]$) as well as producer surplus ($E[PS^{\alpha}]$) and total social surplus ($E[S^{\alpha}]$) for α share of aggregate wind generator ownership.

I use the conventional definition for consumer surplus as the difference in area under the demand curve for a given production level, Q(t), minus the total market value of purchasing that level of output. Therefore, for our linear inverse demand function, we have:

$$CS[Q(t)] = \left[\int_0^{Q(t)} (X - \gamma q)dq\right] - (X - \gamma Q(t))Q(t) = \frac{\gamma Q(t)^2}{2} \tag{27}$$

Given the total production level in **(18)**, we have:

$$CS^{\alpha}[Q_W(t)] = \frac{n^2}{(n+1)^2}\frac{(X-c)^2}{2\gamma} + \frac{n(1-\alpha)(X-c)}{(n+1)^2}Q_W(t) + \frac{\gamma(1-\alpha)^2}{2(n+1)^2}Q_W(t)^2 \tag{28}$$

Producer surplus for a given prodution level (Q(t)) is given by the total revenue minus the total cost of production. Hence:

$$PS[Q(t)] = (X - \gamma Q(t))Q(t) - cQ_P(t) \tag{29}$$

Again taking **(18)** into account, we have:

$$PS^{\alpha}[Q_W(t)] = \frac{n}{(n+1)^2}\frac{(X-c)^2}{\gamma} + \left[\frac{(1-n)(1-\alpha)(X-c)}{(n+1)^2} + c\right] Q_W(t) - \frac{\gamma(1-\alpha)^2}{(n+1)^2} Q_W(t)^2 \tag{30}$$

For the calculation of the social surplus we can either use the objective function in **(3)** or alternatively the sum of the consumer and producer surplus. Then total social surplus is given by:

$$S^{\alpha}[Q_W(t)] = \frac{n(n+2)}{(n+1)^2}\frac{(X-c)^2}{2\gamma} + \left[\frac{(1-\alpha)(X-c)}{(n+1)^2} + c\right] Q_W(t) - \frac{\gamma(1-\alpha)^2}{2(n+1)^2} Q_W(t)^2 \tag{31}$$

Given the above derivations of PS^{α}, CS^{α} and S^{α} expected values are:

$$E[CS^{\alpha}] = \frac{n^2}{(n+1)^2}\frac{(X-c)^2}{2\gamma} + \frac{n(1-\alpha)(X-c)}{(n+1)^2} Q_{W,0} + \frac{\gamma(1-\alpha)^2}{2(n+1)^2}(Q_{W,0}^2 + \sigma^2) \tag{32}$$

$$E[PS^{\alpha}] = \frac{n}{(n+1)^2}\frac{(X-c)^2}{\gamma} + \left[\frac{(1-n)(1-\alpha)(X-c)}{(n+1)^2} + c\right] Q_{W,0} - \frac{\gamma(1-\alpha)^2}{(n+1)^2}(Q_{W,0}^2 + \sigma^2) \tag{33}$$

$$E[S^{\alpha}] = \frac{n(n+2)}{(n+1)^2}\frac{(X-c)^2}{2\gamma} + \left[\frac{(1-\alpha)(X-c)}{(n+1)^2} + c\right] Q_{W,0} - \frac{\gamma(1-\alpha)^2}{2(n+1)^2}(Q_{W,0}^2 + \sigma^2) \tag{34}$$

There are two straightforward results of **(32) - (34)**. First, it follows from **Lemma 4** that the total peakload production and hence the total social surplus is independent of k. Second, the volatility of wind generation (σ^2) has no impact on the expected social surplus when all of the wind generators are owned by the peakload firms (i.e., $\alpha = 1$). This is again because, in both of those cases, the effects of wind generation are fully internalized by the peakload firms.

Proposition 6. *The expected consumer surplus increases whereas the expected producer surplus and the expected social surplus decrease with the volatility of wind generation.*

Proof. It follows from **(30) - (32)** that:

$$\frac{\partial E[CS^\alpha]}{\partial \sigma^2} = \frac{\gamma(1-\alpha)^2}{2(n+1)^2} > 0$$

$$\frac{\partial E[PS^\alpha]}{\partial \sigma^2} = -\frac{\gamma(1-\alpha)^2}{(n+1)^2} < 0$$

$$\frac{\partial E[S^\alpha]}{\partial \sigma^2} = -\frac{\gamma(1-\alpha)^2}{2(n+1)^2} < 0$$

□

Proposition 6 shows that the negative effect of volatility on the producer surplus outweighs the positive effect on the consumer surplus. Therefore the volatility of wind generation (σ^2) negatively affects the expected social surplus. This negative effect is lower in the wind generator ownership case as the internalization of the wind generator dampens the effect of σ^2. Furthermore, the effect of the volatility on the expected consumer, producer and total social surplus decreases with α.

4 Cournot Equilibrium Under Different Renewable Energy Support Schemes

Renewable energy support schemes are instruments to facilitate the deployment, production and use of energy from renewable sources. Although there are a number of renewable energy support schemes, in general, they will result in different returns for the same level of wind generation compared to the no-support case. In other words, under the existence of these support schemes, firms with renewable energy generators will face different profit functions than **(7)**. Therefore, we might see changes to the corresponding first order conditions and hence to the equilibrium outcomes and even the investment decisions. In that regard, Held *et al.* (2014) document and compare different types of renewable support schemes from a theory and real-life applications points of view. Boomsma *et al.* (2012) further investigate how investment decisions in renewable energy change under different support schemes. They specifically look into how feed-in tariffs and renewable energy certificate trading impact investment timing and capacity.

The main assumption in this paper so far has been that the wind energy production is awarded at the market clearing price. This assumption can be relaxed based on the specific renewable support schemes that are adopted in specific markets. Hence, in this section, I study how the Cournot equilibrium and market outcomes change under different renewable support schemes. Specifically, I investigate the effects of two main types of renewable support schemes on the equilibrium outcomes. In summary, a fixed feed-in premium support scheme does not affect the peakload firms production levels and hence market outcomes. However, a feed-in tariff fixes the per unit revenues for wind generation and as a result, the peakload firms with wind generators act as if they do not own any wind generation at all. Therefore, there is an increase in the total production and a decrease in the market price under a feed-in tariff type of support scheme.

4.1 Equilibrium under fixed feed-in premium

Feed-in premium refers to a payment to the owners of wind generators on top the market clearing price. As a result, firms are encouraged to invest in wind generators by gaining extra rents to make up for costs and uncertainties wind generator ownership might bring them. Applying a fixed feed-in premium scheme in the model results in a change in the profit functions for the firms with wind generator ownership. Hence, there will be changes to the corresponding first order conditions.

For any firm $i \in I$, with wind generator ownership, the profit function is:

$$\Pi_i(t) = [X - \gamma(Q_{P,i} + Q_{P,i'} + Q_{P,n-k} + Q_W(t))](Q_{P,i} + \mathbf{A}Q_W(t)) + F_1\mathbf{A}Q_W(t) - cQ_{P,i} \quad (35)$$

where $Q_{P,i'}$ is the aggregate peakload production of the firms with wind generator ownership except for firm i, $Q_{P,n-k}$ is the aggregate peakload production of the firms without wind generator ownership and F_1 is the fixed feed-in premium firm i gets per wind power production.

Following the same steps in **Appendix A.1** the first order condition for firm i entails:

$$Q_{P,i} = \frac{1}{k+1}\left[\frac{X-c}{\gamma} - Q_{P,n-k} - (\mathbf{A}+1)Q_W\right] \quad (36)$$

which is the same expression as the no-support case given in the **Appendix A.1**. Since, the best-response function for any firm j without wind generator ownership would not change either, the resulting equilibrium peakload production levels are going to be the same as **(9)** and **(10)**. Therefore, a fixed feed-in premium has no impact on the market outcomes and the only change would be an increase in the producer surplus. [4]

4.2 Equilibrium under feed-in tariff

Feed-in tariff refers to the payment of a predetermined fixed price to the owners of wind generation instead of the market clearing price for certain number of years. Policy makers determine and announce these fixed tariffs for renewable electricity generation and update it periodically. The main benefit of this approach is to get rid of the price uncertainty that the investors in wind generators face.

[4] A floating feed-in premium might return different results here as there will be changes to F_1 in the profit function. Specifically, if the feed-in premium depends on the production, there will be a different result then **(36)** for the peakload firms with generator ownership. As a result, the equilibrium production and price levels would differ. (See Held *et al.* (2014) for a more detailed discussion on floating feed-in premiums.)

For any firm $i \in I$, with wind generator ownership, the profit function is:

$$\Pi_i(t) = [X - \gamma(Q_{P,i} + Q_{P,i'} + Q_{P,n-k} + Q_W(t))]Q_{P,i} + F_2 \mathbf{A} Q_W(t) - cQ_{P,i} \quad (37)$$

where $Q_{P,i'}$ is the aggregate peakload production of the firms with wind generator ownership except for firm i, $Q_{P,n-k}$ is the aggregate peakload production of the firms without wind generator ownership and F_2 is the feed-in tariff firm i gets per wind power production.

Then the first order condition for firm i entails:

$$Q_{P,i} = \frac{1}{k+1}\left[\frac{X-c}{\gamma} - Q_{P,n-k} - Q_W\right] \quad (38)$$

It is evident that **(38)** does not depend on $\mathbf{A}$. Since the firm j's best-response function would stay the same as before, we have a symmetric equilibrium for peakload production:

$$Q_{P,i} = Q_{P,j} = \frac{X-c}{\gamma(n+1)} - \frac{Q_W}{n+1} \quad (39)$$

Given these peakload production levels, we have the following equilibrium market production and price:

$$Q(t) = \frac{n}{n+1}\frac{X-c}{\gamma} + \frac{Q_W(t)}{n+1} \quad \text{and} \quad P(t) = \frac{X-c}{n+1} - \frac{\gamma Q_W(t)}{n+1} \quad (40)$$

We see from **(39)** that the peakload firms do not internalize their share of wind generation anymore and simply act as if they do not own any wind generation at all. As a result, peakload and total production is higher and market price is lower compared to the no-support case. In other words, a feed-in tariff support scheme eliminates the effects of wind generation ownership on the market outcomes. In the end, although peakload production levels stays the same for all firms, total production and the profits for the firms with wind generators increase.

5 Conclusion

In this paper, I investigate the short term effects of wind generator ownership by the owners of fossil-fueled peakload generators. I use a Cournot oligopoly model to show the effects on the individual and total peakload production levels as well as the market price. I also provide a basic analysis of the start up and shut down decisions of the peakload generators. Furthermore, I investigate the welfare impacts of wind generation ownership and explore the effects of different renewable support schemes on the market outcomes.

The oligopoly model in this paper shows that, wind generator ownership by owners of peakload generators results in significantly lower total peakload production and higher market prices. Moreover, every peakload firm is influenced by the aggregate wind generator ownership. In that regard, while the firms without wind generators increase their peakload production, the firms with wind generators decrease theirs. Furthermore, by internalizing their share of wind generation, peakload firms decrease their total production costs and earn higher profits. In addition, when all wind generators are owned by the peakload firms, the impact of wind generation on the market outcomes vanishes. I further find that the peakload firms that own wind generators ask higher start up and shut down prices under higher levels of wind generator ownership. I additionally show that effect of the volatility of the wind generation on the expected consumer, producer and total social surpluses decreases with the aggregate wind generation ownership due to internalization of the wind generation.

Given the theoretical evidence in this paper, I conclude that wind generator ownership potentially increases the market power of the peakload firms. However this result depends on what type of renewable support schemes are adopted in specific markets. In any case, policy makers and regulators need to take into account the outcomes of the possible ownership structures in the electricity markets as important as the investment in renewable electricity production technologies.

A Appendix Additional Model Details and Results

A.1 Oligopolistic Cournot Equilibrium

Profit function for any firm $i \in I$ is given:

$$\Pi_i(t) = [X - \gamma(Q_{P,i} + Q_{P,i'} + Q_{P,n-k} + Q_W(t))](Q_{P,i} + \mathbf{A}Q_W(t)) - cQ_{P,i}$$

Therefore, firm i's objective is to maximize the profit function:

$$max_{Q_{P,i}}\{\Pi_i(t)\} \tag{41}$$

s.t. $Q_{P,i} \geq 0$.

Then, the first order condition is given by:

$$Q_{P,i} = \frac{1}{2}\left[\frac{X-c}{\gamma} - Q_{P,i'} - Q_{P,n-k} - (\mathbf{A}+1)Q_W\right]$$

By taking $Q_{P,i'} = (k-1)Q_{P,i}$, best-response function for firm i is given by:

$$Q_{P,i} = \frac{1}{k+1}\left[\frac{X-c}{\gamma} - Q_{P,n-k} - (\mathbf{A}+1)Q_W\right]$$

Similarly for any firm $j \in J$, we have:

$$\Pi_j(t) = [X - \gamma(Q_{P,j} + Q_{P,j'} + Q_{P,k} + Q_W(t))]Q_{P,j} - cQ_{P,j}$$

Hence, firm j's objective is to maximize the profit function:

$$max_{Q_{P,j}}\{\Pi_j(t)\} \tag{42}$$

s.t. $Q_{P,j} \geq 0$.

Then the first order condition entails:

$$Q_{P,j} = \frac{1}{2}\left[\frac{X-c}{\gamma} - Q_{P,j'} - Q_{P,k} - Q_W\right]$$

By taking $Q_{P,j'} = (n-k-1)Q_{P,j}$, best-response function for firm j is given by:

$$Q_{P,j} = \frac{1}{n-k+1}\left[\frac{X-c}{\gamma} - Q_{P,k} - Q_W\right]$$

By inserting $Q_{P,j}$ into $Q_{P,i}$, we get the equilibrium quantities:

$$Q^*_{P,j}(t) = \frac{X-c}{\gamma(n+1)} - \frac{1-\alpha}{n+1}Q_W(t)$$

$$Q^*_{P,i}(t) = \frac{X-c}{\gamma(n+1)} - \frac{1-\alpha}{n+1}Q_W(t) - \mathbf{A}Q_W(t)$$

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Market Power and Investment in Electricity Generation

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Abstract

In this paper, we compare the investment timing and investment capacity for the optimal level of investment for a strategic firm and a social planner that have a one-time opportunity to invest in two types of electricity generators. In our paper we do not only focus on the differences in costs for different technologies but also on the differences in operation of those technologies and how those differences impact the optimal investment decisions. In our model, the one-time investment decision requires the determination of demand shock trigger level, choice of technology and level of optimal capacity. We specifically investigate how the investment triggers, optimal capacities and technology choices change with the changes to the investment cost function, demand uncertainty and the level of installed capacity in the market.

In the numerical results, we find that the strategic firm tends to invest at a higher demand trigger level and lower capacity compared to the social

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planner for both the baseload and peakload investment cases. Hence, the strategic firm is expected to invest at a later date while incurring lower investment costs. Furthermore, for both the strategic firm and the social planner, fixed baseload generation is preferable during low uncertainty cases whereas high uncertainty tends to result in the choice of flexible peakload generation. We additionally find that highly convex investment costs greatly diminishes the impact of market power on the investment decisions. We also find that with increased levels of installed capacity and installed capacity ownership, the strategic firm delays the new investment and increases the new investment capacity. However increased share of production in the market for the strategic firm does not necessarily increase its expected profits.

Keywords: Real options, investment, electricity.

JEL Classification: D92, L11, L13, L94

1 Introduction

Investment decisions in electricity markets have been a long lasting focus of researchers. In this paper, we exclusively focus on the investment decisions of different types of electricity generators. Using real options analysis and following Hagspiel et al. (2010) and Huisman and Kort (2012), we compare the investment timing and optimal level of investment for a strategic firm and a social planner in a simplified electricity market. In that regard, we combine investment in electricity generation and real options.

There exists vast real options literature on a firm's optimal investment and capacity decisions. In the seminal works of this area, Pindyck (1988) studies investment decisions by examining the value and cost of incremental investment and Dixit (1992) focuses on the irreversible investment in scale economies. Additionally, Dangl (1999) and Hagspiel *et al.* (2010) investigate a firms investment timing and capacity choice based on the uncertainty of demand shift parameter. Huisman and Kort (2012) further provide a dynamic analysis of entry deterrence/accommodation strategies in a duopoly setting.

In the real options literature we also find studies focusing on investment decisions in electricity markets. Aguerrevere (2005), presents a model of investment under uncertainty that includes time to build, capacity choice and flexibility in the use of the installed capacity, and considers the effect of competition. Liski and Murto (2009) consider a model of capital replacement under uncertainty of energy costs. Boomsma *et al.* (2012) investigate how investment decisions in renewable energy change under different support schemes. Abadie and Chamorro (2012) address the valuation of an operating wind farm and the finite-lived option to invest in such a farm under different reward and/or support schemes.

The options literature provides additional studies that investigates the technology choice in the electricity markets. Nasakkala and Fleten (2004) compute optimal building and upgrading thresholds for gas fired power plant investments; Madlener and Wickart (2007) explain the decision making problem when the decision is between making an irreversible investment in a combined heat-and-power production (cogeneration) system, or to invest in a conventional heat-only generation system (steam boiler); Bobtcheff (2008) studies the investment decision problem of a duopoly with price competition on a market of finite size driven by stochastic shocks on profit; Takashima *et al.* (2010) investigate how an investor makes decisions about timing, sizing, and technology choice.

The main contribution of this paper is to extend the real options literature to allow for the ownership of a generation portfolio of different technologies after an irreversible investment in electricity generation takes place. Contrary to the vast majority of the papers in the literature, the difference in technology choice is not just about the cost of investment or operation. Different technology choices entail different revenue streams and hence a different approach to evaluate the investment decisions. In our paper we do not only focus on the differences in costs for different technologies but also on the differences in operation of those technologies and how those differences impact the optimal investment decisions.

The rest of the paper is organized as follows: In Section 2, we give the aim and formal set up. Additionally, we provide model derivations for the strategic firm and the social planer cases. In Section 3, we give numerical results to the theoretical derivations of Section 2. In Section 4, we provide a brief conclusion on our findings.

2 Model Setup

Our model is an extension of the models studied by Hagspiel *et al.* (2010) and Huisman and Kort (2012). We specifically extend their models to study investment in electricity markets. Compared to their models, our model allows for not only linear but also convex and concave investment costs for the electricity generation investment of a strategic firm and hypothetical social planner. Additionally, the strategic firm in question is allowed to own some level of installed capacity of baseload technology prior to the investment decision. We compare the investment decisions of the strategic firm and hypothetical social planner and explore the effects of market power on the investment decisions of different types of generator investments. We further investigate how the choice of technology changes with respect to certain model parameters.

The starting point of our model is a simplified electricity market that has $K \geq 0$ level of installed capacity already in place. To simplify the model, we assume that all installed capacity is of a single technology. This capacity is always active, producing electricity at full capacity and subject to a constant marginal cost of production $c > 0$. Furthermore, the strategic firm in the industry owns a fraction of the generation from the installed capacity, $A \in [0, 1]$, and has a one-time opportunity to invest in electricity generation.

The sole source of uncertainty in our model is the exogenous demand shock following a *Geometric Brownian Motion*:

$$dX(t) = \alpha X(t)dt + \sigma X(t)dz \tag{1}$$

where α is the drift paramater, σ is the volatility parameter, dt is the increment of time and dz is the increment of a Wiener process.[1] [2]

We assume that there are two types of technologies to choose from: *baseload* and *peakload*. To simplify our derivations and determination of the technology choice, we assume that the decision between these two mutually exclusive

[1]Using this specific stochastic process is a standard assumption in the real options literature. By assuming this dynamic, we can derive closed-form solutions for the options values.

[2]If price or profit uncertainties are used in this context, investment in new generation would have no impact on the existing assets. Therefore demand uncertainty assumption is crucial to assess the relationship between existing assets and new generation investment.

projects is to be made at time zero by the investor. The marginal cost of production for the new generator depends on the choice of technology and satisfies $c_B < c < c_P$, where c_B is the marginal cost for the baseload technology and c_P is the marginal cost for the peakload technology. Therefore, investing in baseload generation entails lower marginal cost of production than the installed capacity. Whereas investing in peakload capacity entails higher marginal cost of production than the installed capacity.

If the baseload type of generator is chosen, the marginal cost of production for the new generator will be low but the generator will always operate at full capacity and never shuts down. However, if the peakload generator is chosen, the marginal cost of production will be high but electricity generation could be costlessly suspended when the demand is low. The investor can then invest in $K_{new} > 0$ level of new capacity and investing in this capacity is subject to fixed cost I and variable cost K_{new}^{λ}. Therefore, total investment cost equals to $I + K_{new}^{\lambda}$ where $\lambda \geq 0$. This investment cost function is convex when $\lambda > 1$, linear when $\lambda = 1$ and concave when $\lambda < 1$.

We further assume that the market price of electricity fluctuates stochastically according to a linear inverse demand function, $D : \mathbb{R}_+ \times \mathbb{R}_+ \to \mathbb{R}$:

$$P(t) = D[X(t), Q(t)] = X(t) - \gamma Q(t) \quad \text{with } \gamma > 0, \tag{2}$$

where $Q(t)$ is the total industry production at time t and $X(t)$ is the stochastically varying demand intercept. [3]

In the following sections we explore the investment decisions of the strategic firm and the social planner when there are two types of technology to choose from: an always-on fixed production technology and another technology that can be costlessly suspended. In the relevant literature, the main distinction between these two types of technologies is that peakload generators to have lower investment costs and higher marginal costs compared to baseload generators (see Joskow (2006)). However, this distinction is not enough to capture the value of flexible production of a peakload generator. Specifically, disregarding the values of option to suspend and option to start up operation will result in undervaluing the peakload generators. This point will be addressed in more detail in the following sections.

[3]Note that we do not impose any restrictions on inverse demand function. Therefore, depending on the model parameters and the investment decisions, market prices could get negative.

2.1 Strategic Firm

In this section, we explore the investment decisions of the strategic firm. Our aim in this section is to show how the derivations differ with the technology choice.

2.1.1 Baseload Investment

In this section, we consider the investment decision of the strategic firm when the technology in question is the always-on baseload technology. The strategic firm's decision is to maximize the total discounted value of its investment by choosing a level of demand shock level, X_{SF}, as the investment trigger and choosing a level of capacity to invest, K_{SF}, at the time when the stochastic demand shock hits the corresponding trigger level. The strategic firm starts utilizing its new generator upon its investment and is assumed not to face any entry threats. Therefore, the strategic firm in this model does not have to concern itself with preemption or entry deterrence strategies. Let V denote the value of the firm. Then the strategic firm faces an optimal stopping problem which can be formally given as:

$$V(X) = sup_{\tau_{SF} \geq 0, K_{SF} \geq 0} E \left[\int_0^{\tau_{SF}} e^{-rt} \Pi_{SF}^0(t)dt + \int_{\tau_{SF}}^{\infty} e^{-rt} \Pi_{SF}^1(t)dt \right. \\ \left. -e^{-r\tau_{SF}}(I + K_{SF}^{\lambda}) \mid X(0) = X \right] \tag{3}$$

as we assume that $X(0) < X_{SF}$ and define:

$$\tau_{SF} = inf \left\{ t \geq 0 | X(t) \geq X_{SF} \right\}, \tag{4}$$

where r is the exogenously specified riskless rate of return and τ_{SF} is the time of investment. Furthermore, $\Pi_{SF}^0(t)$ is the instantaneous profit function of the strategic firm until the time of investment and $\Pi_{SF}^1(t)$ is the instantaneous profit function of the strategic firm afterwards. Therefore the first term in the objective function is the discounted value of the profits from the installed capacity prior to investment, the second term is the discounted value of the profits from both the installed capacity and the new baseload generation, and the last term is the discounted cost of investment.

Assuming that the strategic firm invests in K_{SF} level of baseload capacity, total electricity production of the strategic firm before the investment, $t <$

τ_{SF}, is simply the production from the installed capacity, AK. Whereas the total electricity production of the strategic firm after the investment, $t \geq \tau_{SF}$, is the sum of the production from the share of installed capacity and the production from the new baseload capacity, $AK + K_{SF}$. Hence the total production of the strategic firm is:

$$Q^{SF}(t) = \begin{cases} AK & \text{if } t < \tau_{SF} \\ AK + K_{SF} & \text{if } t \geq \tau_{SF} \end{cases} \tag{5}$$

Note that after the investment takes place, the total electricity production will always be equal to $AK + K_{SF}$ even if the momentary demand shock falls below the trigger level (i.e., $X < X_{SF}$).

Consequently, the instantaneous profit function of the strategic firm before the investment (i.e., $t < \tau_{SF}$) is simply the profits from the installed capacity:

$$\Pi^0_{SF}(t) = (X(t) - \gamma K)AK - cAK \tag{6}$$

and the profit function after the investment (i.e., $t \geq \tau_{SF}$) is the sum of the profits from the installed capacity and the new baseload capacity:

$$\begin{aligned} \Pi^1_{SF}(t) &= (X(t) - \gamma(K + K_{SF}))(AK + K_{SF}) - c_B K_{SF} - cAK & (7) \\ &= \Pi^0_{SF}(t) + X(t)K_{SF} - (\gamma(A+1)K + \gamma K_{SF} + c_B)K_{SF} & (8) \end{aligned}$$

Note that after the investment of new baseload capacity there are additional profits whenever $X(t) > \gamma(A+1)K + \gamma K_{SF} + c_B$.

2.1.2 Value Function and Additional Model Derivations

Now that we know the profit function of the strategic firm, the next step is to determine the value function before and after the investment. At the time of investment, following Huisman and Kort (2012), the value function is given by:

$$E\left[\int_0^\infty e^{-rt}\Pi^1_{SF}(t)dt - (I + K^\lambda_{SF}) \mid X(0) = X\right] \tag{9}$$

On the other hand, before the investment, the value function equals the sum of the option value to invest and the discounted value of the profits coming from the installed capacity. By using dynamic programming, the option value of the investment $F^M(X, K_{SF})$ satisfies:

$$F^M(X, K_{SF}) = e^{-rdt} E\left[F^{SF}(X(t), K_{SF}) + dF^{SF}(X(t), K_{SF}) \mid X(0) = X\right] \tag{10}$$

Using standard real options techniques (i.e., using Ito's Lemma to expand the right hand side and then neglecting the terms that go to zero), the option value to invest will be the solution to the ordinary differential equation (see, Dixit and Pindyck (1994), Chp. 4):

$$\frac{1}{2}\sigma^2 X^2 \frac{d^2 F^{SF}}{dX^2} + \alpha X \frac{dF^{SF}}{dX} - rF^{SF} = 0 \tag{11}$$

Hence, excluding the bubble solution (i.e., the term that goes to infinity), the option value for the strategic firm who is to invest in K_{SF} level of new capacity is of the form:

$$B(K_{SF})X^{\beta} \quad \text{for} \quad X < X_{SF} \tag{12}$$

where $\beta > 1$ is the positive root of the quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{13}$$

Furthermore, the discounted value of the profits coming from the installed capacity before the investment is given by:

$$E\left[\int_0^{\infty} e^{-rt}\Pi^0_{SF}(t)dt\right] \tag{14}$$

Hence, combining **(12)** and **(14)**, gives the value function before the investment as:

$$B(K_{SF})X^{\beta} + E\left[\int_0^{\infty} e^{-rt}\Pi^0_{SF}(t)dt\right] \tag{15}$$

We assume that there exists an optimal demand shock trigger level X^*_{SF} and optimal investment capacity K^*_{SF} such that the supremum in **(3)** is realized.

Then by combining **(7)**, **(9)** and **(15)** we get the value function[4]:

$$V(X) = \begin{cases} BX^{\beta} + \dfrac{AK}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} & \text{if } X < X^*_{SF} \\ \dfrac{AK + K^*_{SF}}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda}) & \text{if } X = X^*_{SF} \\ -\dfrac{(\gamma(A+1)K + \gamma K^*_{SF} + c_B)K^*_{SF}}{r} & \end{cases} \tag{16}$$

It can be seen from the above function that, when $X(t) < X^*_{SF}$, it is more profitable to wait and hence the strategic firm only receives the profits coming from its conventional generators. On the other hand, the first time $X(t) = X^*_{SF}$ holds, the strategic firm incurs the total investment cost $I + K^{\lambda}_{SF}$ and starts receiving the additional profits coming from the new baseload generator.

Proposition 1. *The optimal investment threshold X^*_{SF} and the optimal investment capacity K^*_{SF} satisfy* [5]*:*

$$\frac{X^*_{SF}}{r-\alpha} - \frac{(\gamma(A+1)K + 2\gamma K^*_{SF} + c_B)}{r} - \lambda {K^*_{SF}}^{\lambda-1} = 0 \tag{17}$$

$$\frac{\beta-1}{\beta}\frac{K^*_{SF}}{r-\alpha}X^*_{SF} - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_B)K^*_{SF}}{r} - I - {K^*_{SF}}^{\lambda} = 0 \tag{18}$$

Proof of **Proposition 1** is given in **Appendix A.1**.

[4] If the technology choice is to be made at a later date than $t = 0$, the value function before the investment would include the option value to invest in both types of technologies. In other words, both options would be alive until one of the mutually exclusive technologies is chosen (see Takashima *et. al.* (2010)).

[5] These equations are only sufficient conditions and the equations may have multiple solutions that does not necessarily give the same expected value. But the propositions in this paper make it possible to determine a finite number of candidates, where the optimal solution returns the highest expected value for the total assets. See **Appendix** for details.

2.1.3 Peakload Investment

In this section, we consider the investment decision of the strategic firm when the technology in question is the costlessly suspendible peakload technology. Since we are dealing with a different type of generator than before, the strategic firm is to receive a different profit flow for the peakload technology case. Therefore the objective and the value functions in this case different than the previous section.

We do not have a straightforward value function for the peakload investment case as the peakload generation can be costlessly suspended. Therefore to simplify our derivations, we divide the value function in two: the value function before the investment and the value function after the investment. Since the value function before the investment requires the determination of the value of an active generator, we start the derivation by finding the value function after the investment. So, we first look at the production levels after the investment takes place. Since the generation can be suspended, the total production of the strategic firm after the investment is:

$$Q^M(t) = \begin{cases} AK & \text{if } X < \underline{X}_{SF} \\ AK + K_{SF} & \text{if } X \geq \underline{X}_{SF} \end{cases} \tag{19}$$

where $\underline{X}_{SF}$ is the demand shock level at which the peakload operation is costlessly started up or shut down and defined by:

$$\begin{aligned} \underline{X}_{SF} &= \left\{X(t)|\Pi^0_{SF}[X(t), AK] = \Pi^1_{SF}[X(t), AK + K_{SF}], \forall t\right\} &(20)\\ &= \gamma(A+1)K + \gamma K_{SF} + c_P &(21) \end{aligned}$$

Since the peakload generator can be suspended costlessly, the strategic firm suspends the operation when the demand is so low that the profits when the peakload generator is active is lower than the profits when the peakload generator is idle. Furthermore, in the case of ownership of a generation portfolio, $A > 0$, the strategic firm starts up and suspends operation at a single threshold where the market price significantly exceeds the marginal cost of peakload generation. This strategy is used to offset the negative impact of the new investment on the market price.

Given **(19)**, the profit function of the strategic firm before the investment or when the generation is suspended is simply the instantaneous profits from the installed capacity:

$$\Pi^0_{SF}(t) = (X(t) - \gamma K)AK - cAK \tag{22}$$

and the profit function when the peakload generator is active is the sum of the profits from the installed capacity and the peakload capacity:

$$\begin{aligned}\Pi^1_{SF}(t) &= (X(t) - \gamma(K + K_{SF}))(AK + K_{SF}) - c_P K_{SF} - cAK & (23)\\ &= \Pi^0_{SF}(t) + X(t)K_{SF} - (\gamma(A+1)K + \gamma K_{SF} + c_P)K_{SF} & (24)\end{aligned}$$

Given the above profit functions the value function after the investment is given by:

$$\tilde{V}(X) = \begin{cases} CX^{\beta_1} + \dfrac{AK}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} & \text{if } X \leq \underline{X}_{SF} \\[2ex] DX^{\beta_2} + \dfrac{AK + K^*_{SF}}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} & \text{if } X > \underline{X}_{SF} \\[2ex] -\dfrac{(\gamma(A+1)K + \gamma K^*_{SF} + c_P)K^*_{SF}}{r} & \end{cases} \tag{25}$$

where DX^{β_2} is the option value to suspend operation and CX^{β_1} is the option value to start up operation. Furthermore, $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{26}$$

Note that **(25)** is only the value function after the investment. In order to find the option value to invest and ultimately derive the optimal investment strategy, we need to derive the value function before the investment and combine it with **(25)**.

The derivation of the value before the investment follows the same steps as **(25)**. Therefore it is simply of the same form as the value function when the peakload generation is suspended, i.e. $X \leq \underline{X}_{SF}$. The only difference is the constant found in the option value to invest due to existence of investment cost. Specifically we have the value function before the investment:

$$V(X) = \begin{cases} LX^{\beta_1} + \dfrac{AK}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} & \text{if } X < X^*_{SF} \\ DX^{\beta_2} + \dfrac{AK + K^*_{SF}}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda}) & \text{if } X = X^*_{SF} \\ -\dfrac{(\gamma(A+1)K + \gamma K^*_{SF} + c_P)K^*_{SF}}{r} & \end{cases} \quad (27)$$

here X^*_{SF} is the optimal demand shock trigger level where K^*_{SF} level of investment in new peakload capacity takes place, $I + K^*_{SF}$ is the cost of investment, DX^{β_2} is the option value to suspend operation and LX^{β_1} is the option value to invest.

Remark 2. *Note that at the time of investment, the strategic firm have two states of production to choose from. It can either have a suspended or active peakload generator upon the investment. However, choosing to have a suspended generator does not return any additional profits whereas it requires early incurrence of the investment cost. Therefore by waiting longer to invest and choosing to produce electricity with the new generator upon the investment, the strategic firm can earn additional profits. Furthermore since the investment would take place at a later date, the discounted cost of investment of the new geerator would be lower for the strategic firm. Hence, we always have* $X^*_{SF} \geq \underline{X}_{SF}$.

Proposition 3. *The optimal investment threshold* X^*_{SF} *and the optimal investment capacity* K^*_{SF} *satisfy:*

$$D'(K^*_{SF}){X^*_{SF}}^{\beta_2} + \frac{X^*_{SF}}{r-\alpha} - \frac{(\gamma(A+1)K + 2\gamma K^*_{SF} + c_P)}{r} - \lambda {K^*_{SF}}^{\lambda-1} = 0 \quad (28)$$

$$\frac{\beta_1-\beta_2}{\beta_1}D(K^*_{SF}){X^*_{SF}}^{\beta_2} + \frac{\beta_1-1}{\beta_1}\frac{K^*_{SF}}{r-\alpha}X^*_{SF} - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_P)K^*_{SF}}{r} - I - {K^*_{SF}}^{\lambda} = 0 \quad (29)$$

Proof of **Proposition 2** is given in **Appendix A.2**.

Remark 4. *Apart from the marginal costs, the difference between **Proposition 1** and **Proposition 2** is the additional terms in **Proposition 2** that uses the option value to suspend peakload generation,* DX^{β_2}. *This distinction shows that when comparing the value or investment decisions of the generators with fixed and flexible generation, focusing simply on the differences on marginal and investment costs is not sufficient. Disregarding the values of option to suspend and option to start up operation will result in undervaluing the peakload generators.*

2.2 Social Planner

In this section, we investigate the social planner's problem. The aim is to see, with the same set up as before, how the social planner's optimal actions differ from the strategic firm's. For the social planner's problem, total discounted expected social surplus is to be maximized. In other words, the social planner maximizes the sum of producer surplus and consumer surplus. In that regard, we use the same approach as Dixit and Pindyck (1994, Chapter 9). First, we define the area under the demand curve for a given production level, $Q(t)$, by:

$$U[Q(t)] = \int_0^{Q(t)} D[q]dq = \int_0^{Q(t)} (X - \gamma q)dq = XQ(t) - \frac{\gamma Q(t)^2}{2} \tag{30}$$

Then total social surplus for a given production level, $Q(t)$, is:

$$S[Q(t)] = U[Q(t)] - C[Q(t)] \tag{31}$$

where $C[Q(t)]$ denotes the total cost of current production. In this setup, instantaneous social surplus at time t, $S[Q(t)]$, will replace the profit flow of a firm. Therefore, derivations will follow the same steps as the case of the strategic firm.

2.2.1 Baseload Investment

Let W denote the value of the social planner, then the optimal stopping problem of the social planner is:

$$\begin{aligned} W(X) = sup_{\tau_{SP} \geq 0, K_{SP} \geq 0} E \bigg[\int_0^{\tau_{SP}} e^{-rt} S^0(t)dt + \int_{\tau_{SP}}^{\infty} e^{-rt} S^1(t)dt \\ -e^{-r\tau_{SP}}(I + K_{SP}^{\lambda}) \mid X(0) = X \bigg] \end{aligned} \tag{32}$$

as we assume that $X(0) < X_{SP}$ and define:

$$\tau_{SP} = inf \left\{ t \geq 0 | X(t) \geq X_{SP} \right\}, \tag{33}$$

where τ_{SP} is the time of investment and X_{SP} is the trigger capacity factor level when K_{SP} level of generator investment takes place. Furthermore, $S^0(t)$ is the instantaneous social surplus until the investment and $S^1(t)$ is the instantaneous social surplus afterwards. Therefore the first term in the objective function is the discounted value of the social surplus from the installed capacity prior to investment, the second term is the discounted value of the social surplus from both the installed capacity and the new generation, and the last term is the discounted cost of investment.

Assuming that the social planner invests in K_{SP} level of new baseload capacity, the total production before and after the investment are:

$$Q^{SP}(t) = \begin{cases} K & \text{if } t < \tau_{SP} \\ K + K_{SP} & \text{if } t \geq \tau_{SP} \end{cases} \tag{34}$$

Note that as the social planner aims to maximize the total social surplus based on the total production and not just the producer surplus, the value A does not have an impact on the social planner's production levels.

Consequently, the total social surplus before the investment, $t < \tau_{SP}$, is:

$$S^0(t) = XK - cK - \frac{\gamma}{2}K^2 \tag{35}$$

and the total social surplus after the investment, $t \geq \tau_{SP}$, is:

$$\begin{aligned} S^1(t) &= X(K + K_{SP}) - cK - c_B K_{SP} - \frac{\gamma}{2}(K + K_{SP})^2 & (36) \\ &= S^0(t) + XK_{SP} - c_B K_{SP} - \gamma K K_{SP} - \frac{\gamma}{2}{K_{SP}}^2 & (37) \end{aligned}$$

2.2.2 Value Function and Additional Model Derivations

In this section, we follow the same steps as the case of the strategic firm. We start with the value function at the time of investment which is given by:

$$E\left[\int_0^{\infty} e^{-rt} S^1(t)dt - (I + K_{SP}^{\lambda}) \mid X(0) = X\right] \tag{38}$$

Before the investment, the value function equals the sum of the option value to invest and the discounted value of the social surplus coming from the installed capacity. Therefore, following the same steps as the case of the strategic firm gives the value function before the investment as:

$$G(K_{SP})X^{\beta} + E\left[\int_0^{\infty} e^{-rt} S^0(t)dt\right] \tag{39}$$

Again, by following the same steps in the previous section, the value function for the social planner who invests in K_{SP} is given by:

$$W(X) = \begin{cases} GX^{\beta} + \dfrac{K}{r-\alpha}X - \dfrac{\gamma K^2 + 2cK}{2r} & \text{if } X < X_{SP}{}^* \\ \dfrac{K + K_{SP}^*}{r-\alpha}X - \dfrac{\gamma(K + K_{SP}^*)^2 + 2cK + 2c_B K_{SP}^*}{2r} & \text{if } X = X_{SP}{}^* \\ -(I + K_{SP}^*{}^{\lambda}) & \end{cases} \tag{40}$$

where, $\beta > 1$ is the positive root of the following quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{41}$$

It can be seen from the above value function that, when $X < X_{SP}^*$, it is not optimal to invest yet and hence the social planner only receives the profits coming from its conventional generators. On the other hand, the first time $X = X_{SP}^*$ holds, the social planner incurs the total investment cost $I + K_{SP}{}^{\lambda}$ and starts benefiting from the additional social surplus coming from the new investment.

Proposition 5. *The investment threshold X_{SP}^* and the optimal investment capacity K_{SP}^* satisfy:*

$$\frac{X_{SP}^*}{r-\alpha} - \frac{\gamma K + \gamma K_{SP}^* + c_B}{r} - \lambda K_{SP}^*{}^{\lambda-1} = 0 \tag{42}$$

$$\frac{\beta-1}{\beta}\frac{K_{SP}^* X_{SP}^*}{r-\alpha} - \frac{(2\gamma K + \gamma K_{SP}^* + 2c_B)K_{SP}^*}{2r} - I - K_{SP}^*{}^{\lambda} = 0 \tag{43}$$

Proof of **Proposition 3** follows the same steps as **Proposition 1** and it is given in **Appendix A.3**.

2.2.3 Peakload Investment

As we have explained in the case of the strategic firm, the value function for the social planner changes with the technology choice. Following the same steps as before, the value function for the case of peakload generation for the social planner after the investment is:

$$\tilde{W}(X) = \begin{cases} HX^{\beta_1} + \frac{K}{r-\alpha}X - \frac{\gamma K^2 + 2cK}{2r} & \text{if } X \leq \underline{X}_{SP} \\ JX^{\beta_2} + \frac{K + K^*_{SP}}{r-\alpha}X - \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r} & \text{if } X > \underline{X}_{SP} \\ -\frac{\gamma K^2 + 2cK}{2r} & \end{cases} \tag{44}$$

where $\underline{X}_{SP}$ is the demand shock level that the peakload operation is costlessly started up or shut down, JX^{β_2} is the option value to suspend operation and CX^{β_1} is the option value to start up operation. Furthermore, $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the following quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{45}$$

where

$$\begin{aligned} \underline{X}_{SP} &= \left\{X(t)|S^0[X(t), K] = S^1[X(t), K + K_{SP}], \forall t\right\} && (46) \\ &= \gamma K + c_P + \frac{\gamma}{2}K_{SP} && (47) \end{aligned}$$

Furthermore the value function before the time of new peakload investment is given by:

$$W(X)=\begin{cases} MX^{\beta_1}+\dfrac{K}{r-\alpha}X-\dfrac{\gamma K^2+2cK}{2r} & \text{if } X<X_{SP}^* \\ JX^{\beta_2}+\dfrac{K+K_{SP}^*}{r-\alpha}X-\dfrac{\gamma K^2+2cK}{2r}-(I+{K_{SP}^*}^{\lambda}) & \text{if } X=X_{SP}^* \\ -\dfrac{(\gamma K_{SP}^*+2\gamma K+2c_P)K_{SP}^*}{2r} & \end{cases} \tag{48}$$

where X_{SP}^* is the trigger demand shock level that the investment in new peakload capacity takes place, JX^{β_2} is the option value to suspend operation and MX^{β_1} is the option value to invest.

Proposition 6. *The investment threshold X_{SP}^* and the optimal investment capacity K_{SP}^* satisfy:*

$$J'(K_{SP}^*){X_{SP}^*}^{\beta_2}+\frac{X_{SP}^*}{r-\alpha}-\frac{(\gamma K+\gamma K_{SP}^*+c_P)}{r}-\lambda {K_{SP}^*}^{\lambda-1}=0 \tag{49}$$

$$\frac{\beta_1-\beta_2}{\beta_1}J(K_{SP}^*){X_{SP}^*}^{\beta_2}+\frac{\beta_1-1}{\beta_1}\frac{K_{SP}^*}{r-\alpha}X_{SP}^*-\frac{(\gamma K_{SP}^*+2\gamma K+2c_P)K_{SP}^*}{2r} -I-{K_{SP}^*}^{\lambda}=0 \tag{50}$$

Proof of **Proposition 4** follows the same steps as **Proposition 2** and it is given in **Appendix A.4**.

3 Results

In this section, we present numerical results that allow us to evaluate and compare findings in **Section 2**. The main aim of this section is to show how changes in certain parameters affect investment triggers and optimal capacities. We focus on how these effects differ for the strategic firm and the social planner. We further investigate for which parameters one technology is to be chosen over the other.

The nature of our findings and the wide range of parameters we utilize necessitate the use of numerical methods. We use the software *Maple* to obtain our numerical results. One important point in our model is that, for the peakload investment case, we might obtain multiple solutions to choose from. In such cases, we simply choose the solution which returns the highest discounted expected value for the total investment of both types of investors. Existence of multiple solutions may result in jumps in some of the graphs we present in the following section.

Another point regarding the graphs in this section is about the feasibility of the investment decision. By nature, a firm would not make an investment if the resulting expected value of that investment is negative. Therefore, in such a case, the investment would not take place. For instance, as the installed capacity in the market prior to the investment increases, corresponding optimal investment decision might return negative expected value. In such a situation, we conclude that the investment itself is not optimal and never takes place, but for reasons of completeness we still present how the increase in the installed capacity affect the expected value even after it becomes negative.

To summarize our findings in this section, the strategic firm tends to invests at a higher demand trigger level and lower capacity compared to the social planner for both the baseload and peakload investment cases. Hence, the strategic firm is expected to invest at a later date while incurring lower investment cost. For both types of investors, baseload generation is preferable during low installed capacity and uncertainty cases whereas high installed capacity and uncertainty tends to result in peakload generation. This result points out that during the times of low uncertainty, the need for flexible generation is low as well. But for high uncertainty cases the peakload generation becomes more favorable as the flexibility is more likely to be used by suspending operation to avoid very low market prices.

3.1 Impact of Cost Function

Table 1 shows that how the nature of investment cost function affect investment triggers and capacities for the strategic firm and the social planner. For concave investment cost, the cost of investing in capacity would be lower than in the linear and convex cost cases. In other words, under concave investment cost, the cost of the marginal capacity is lower than the other two cases. Therefore, we may expect to have higher level of capacity investment from both types of investors for the concave investment cost case as it would be cheaper to build generators. This intuition has also been underlined in Hagspiel *et al.* (2010). **Figure 1** supports this intuition as we observe the level of investment to almost always decrease as the cost function becomes more convex. When the investment takes place for relatively low levels of demand shock trigger while we see very high levels of capacity investment for both the strategic firm and social planner. However, as it becomes more costly to invest, the investment is in general delayed for both cases and level of investment decreases.[6] We see that the difference in trigger and capacities decrease for both technologies and investor types as λ increases. These results show that the extent of market power and the difference between the optimal decisions of both types of investors diminishes as the investment in new capacity becomes very costly.

[6]These findings are in line with Hagspiel *et al.* (2010) too.

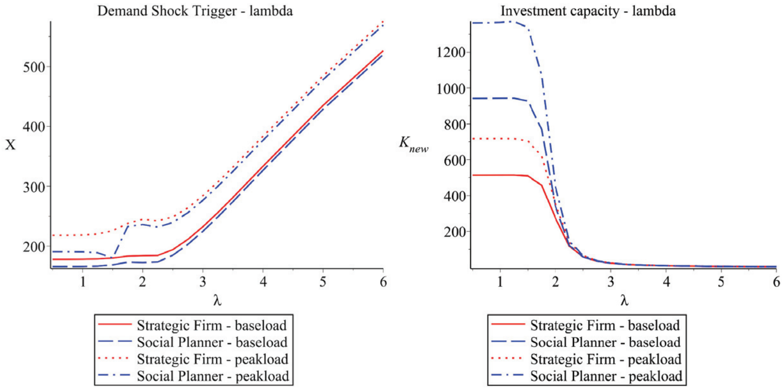

Figure 1: *Investment Triggers and Capacities based on* λ *(For* $A = 0.5$*,* $K = 100$*,* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\sigma = 0.1$ *and* $\gamma = 0.1$*).*

From **Table 1**, we further see that the strategic firm tends to invest at a higher trigger level and at a lower capacity than the social planner. However for high values of λ investment capacities for the strategic firm and the social planner become very close. These findings are valid for both the baseload and peakload generation investment cases. Furthermore when we focus on both types of investors we observe that if the peakload generation is chosen over the baseload generation, the investment capacity and the investment trigger levels are higher. In other words, both types of investors waits longer, invests in higher capacity and incurs a higher investment cost due to bigger investment capacity if it chooses to invest in peakload capacity to enjoy a more flexible production. This result is mainly due to the high levels of uncertainty that makes the peakload generation preferable and a higher marginal cost of production. To benefit most from the high uncertainty both types of investors choose to delay investment and invest in bigger capacity. We further discuss this issue and we investigate how the technology choice is made in **Section 3.4**.

Table 1: *Investment Triggers and Capacities based on the nature of investment cost (For $A = 0.5$, $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$ and $\gamma = 0.1$).*

	Baseload plant				Peakload plant			
λ	K^*_{SF}	K^*_{SP}	X^*_{SF}	X^*_{SP}	K^*_{SF}	K^*_{SP}	X^*_{SF}	X^*_{SP}
0.50	513.97	942.52	178.02	165.83	717.29	1363.4	218.16	190.86
0.75	514.09	942.75	178.05	165.86	717.43	1364	218.25	190.83
1.00	514.38	943.4	178.18	166	717.74	1366.2	218.62	190.56
1.25	514.47	943.77	178.64	166.56	717.2	1371.5	220.24	188.86
1.50	508.68	927.88	180.11	168.62	705.06	1337.8	225.87	180.15
1.75	456.99	769.38	183.33	173.25	620.09	1072.1	237.92	232.7
2.00	274	339.3	184.14	172.61	354.08	448.87	244.8	236.04
2.25	116.98	121.39	184.46	173.52	139.34	145.65	242.16	231.69
2.50	57.585	57.729	194.19	184.88	64.423	64.753	248.72	239.53
2.75	34.169	34.056	211.17	202.89	36.827	36.75	263.96	255.72
3.00	22.994	22.906	232.39	224.72	24.235	24.158	284.18	276.52
3.25	16.82	16.763	256.12	248.82	17.481	17.429	307.25	299.96
3.50	13.04	13.003	281.27	274.23	13.428	13.393	331.95	324.9
4.00	8.811	8.7936	333.33	326.59	8.9758	8.9591	383.39	376.64
5.00	5.2757	5.27	435.05	428.58	5.3257	5.3202	484.45	477.97
6.00	3.8215	3.8188	526.27	519.92	3.8439	3.8413	575.33	568.97

3.2 Impact of Uncertainty

After we observe how the nature of the investment cost function affects the optimal investment decisions, we now focus on the comparison of the optimal investment decisions of the strategic firm and the social planner for specific levels of λ. In that regard, we extend Huisman and Kort (2012)'s results which are just based on linear investment cost. **Figure 2** reveals how investment triggers and optimal capacities change with the uncertainty (i.e., σ) under concave investment cost as $\lambda = 0.5$ (See **Appendix** for the figures for $\lambda = 1$ and $\lambda = 2$). We can see that the demand triggers and the optimal capacities tend to increase with the uncertainty for both types of investors. These results are in line with the relevant literature (e.g., Dixit and Pindyck (1994)) that high uncertainty increases the optimal capacity levels to benefit from possible high prices and it increases the incentive to delay investment to gather more information prior to the investment.

We see that when both types of investors choose to invest in peakload generator the optimal investment capacity will be higher than the corresponding baseload generator investment. This strategy helps the strategic firm to gain even higher revenues during the high demand periods. We further see from the **Figure 2** that for relatively low levels of uncertainty, the demand shock trigger for the peakload generator case is higher. On the other hand, for relatively high levels of uncertainty, investment in peakload generator would occur at a lower demand shock trigger level. We have such a result because the potential benefits of flexible peakload generation offset the high investment and marginal costs during times of sufficiently high levels of uncertainty.

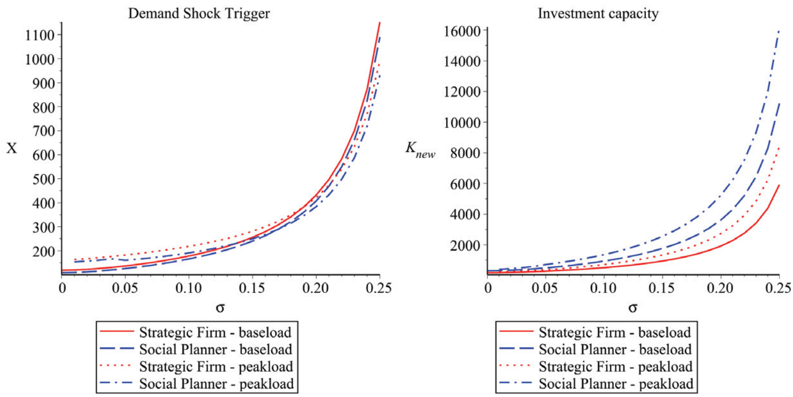

Figure 2: *Investment Triggers and Capacities based on uncertainty (For* $A = 0.5$, $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\gamma = 0.1$ *and* $\lambda = 0.5$*).*

3.3 Impact of Installed Capacity

In this section we investigate how the level of installed capacity affects the optimal investment decisions. We first take a look at the optimal investment triggers and capacities for the case of $A = 0.5$. Impact of the partial ownership of the installed capacity in the market could only be considered effective for the strategic firm case as the the social planner does not maximize the profits but the social surplus (Note that the derivation for the social planner case does not contain the parameter A). Later, we also take a look into the effect of the value A itself on the optimal decisions.

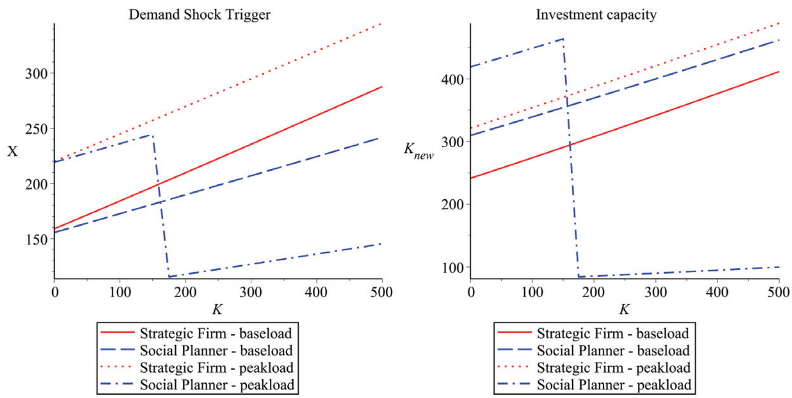

Figure 3: *Investment Triggers and Capacities based on installed capacity (For* $A = 0.5$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ *and* $\lambda = 2$*).*

We see from **Figure 3** that, except for the social planner's peakload investment case, as the level of installed capacity, K, increases the investment triggers and optimal capacities increase as well. We have such a result because higher levels of installed capacity results in lower market prices prior to the new capacity investment. Hence the strategic firm and the social planner choose to wait for higher market prices before the investment takes place. In order to fully benefit from the high market prices resulted by waiting, the strategic firm and the social planner choose to increase the level of new capacity as well. However for the social planner's peakload investment case, we have a slightly different result. What we observe is, the investment trigger and capacity increase with K up to some point. Afterwards, we see see a downwards jump because when K is close to 200, the social planner invests almost immediately at a very low capacity to maximize the expected social surplus. This welfare maximizing decision can be seen more clearly in **Figure 4**.

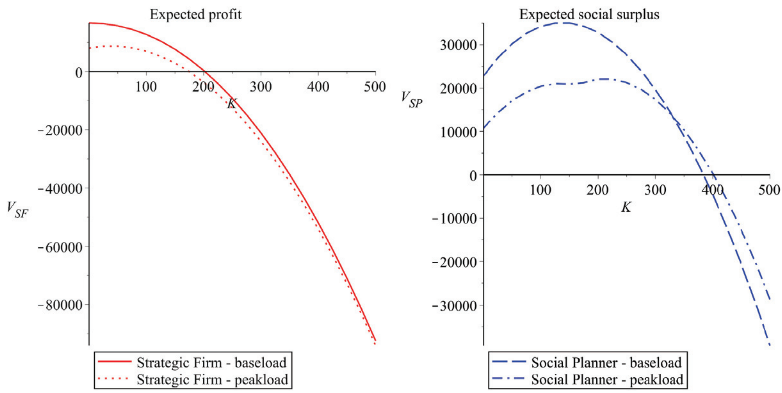

Figure 4: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For $A = 0.5$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 2$).*

Figure 4 shows that the strategic firms expected profits has a tendency to decrease with the level of installed capacity. This is simply because of the increased level of installed capacity paired with the new capacity investment driving the market price down. However for the social planner, we first see the expected social surplus to increase with the installed capacity up to some point and decrease afterwards. This effect is simply due to the increase in the consumer surplus as the increase in the level of installed capacity drives the market price down. When we further focus on the social planners expected social surplus curve for peakload generation, we see a kink in the curve at the same point we see the downwards jump in **Figure 3**. As was mentioned, right until the moment of the kink, a first set of solutions result in the higher expected social surplus but after the kink a second set of solutions start to provide even higher expected social surplus. Hence we observe a jump in **Figure 3** and a kink in **Figure 4**. **Figure 4** also shows that the expected profits becomes negative for a lower level of installed capacity than the social planner. As a result, for relatively high levels of installed capacity, the investment may not be profitable for the strategic firm whereas the social planner may still choose to go ahead with the investment.

In **Figure 5** below we see that the investment triggers and capacity levels increase with A for the strategic firm but not for the social planner. Because, the social planner maximizes the total social surplus based on the total production in the market. Therefore ownership of the installed capacity does not have an impact on the social planner's decision. On the other hand, as the strategic firm owns more and more of the installed capacity in the market, the investment is delayed and a higher level of capacity is chosen to be invested. This behavior is observed for all values λ. This result is due to the strategic firm's reluctance to cannibalize its profits from the installed capacity. When the strategic firm owns more of the installed capacity, undertaking an investment at low levels of demand will decrease the profits from the installed capacity significantly. Instead, the strategic firm waits the demand to be relatively high before investment. And for high levels of demand, the strategic firm becomes better off by investing in bigger capacities

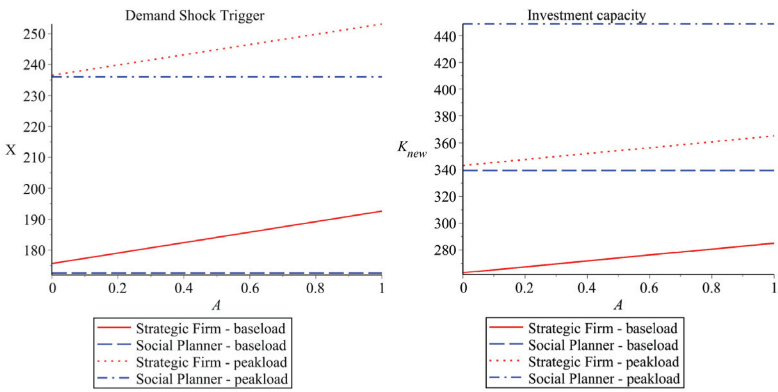

Figure 5: *Investment Triggers and Capacities based on installed capacity based on A (For $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 2$).*

The results we observe in **Figure 5** have actually two opposing impacts from welfare maximization point of view. We see from the **Figure 5** that the demand shock triggers move away from the socially optimal outcome whereas the investment capacities move closer to their socially optimal counterparts. We further see from the **Figure 6** that there is an overall decrease in the total social surplus with an increase in the ownership A. This result is natural due to the negative impact of the increase in the demand shock trigger dominating the positive impact of the investment capacity. However this result does not necessarily guarantee an increase in the profits of the strategic firm. We can see from **Figure 6** that the ownership of the installed capacity is beneficial to the strategic firm only when it is paired with the ownership of a peakload generator for $\lambda = 2$ case. Therefore we conclude that an increase in the ownership of the total production in the market does not necessarily result in higher profits for the strategic firm.

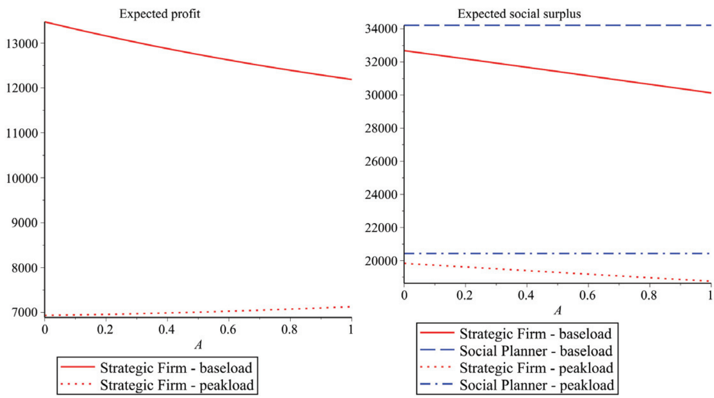

Figure 6: *Expected Profit and Social Surplus for the Strategic Firm (For* $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ *and* $\lambda = 2$*).*

3.4 Technology Choice

Until this point in this paper, we explored the idea of investing in different types of technologies exclusively. In other words, we separately investigated what would happen if both types of investor invests either in baseload or peakload technology. However, in a realistic scenario, both types of investors would choose to invest in one technology over the other. In this section, by focusing on the uncertainty parameter (σ), we explore to find what will be the technology choice for varying levels of σ.

Our methodology in this section is simply to compare the discounted value of the total assets for both types of investors. As mentioned before, to simplify the determination of the technology choice, we compare the expected discounted values of both technologies at time zero. Then both types of investors make their optimal technology choices, based on the evaluation of their corresponding objectives. So, the strategic firm chooses to invest in the technology that returns higher expected profit whereas the social planner chooses to invest in the technology that returns higher expected social surplus.

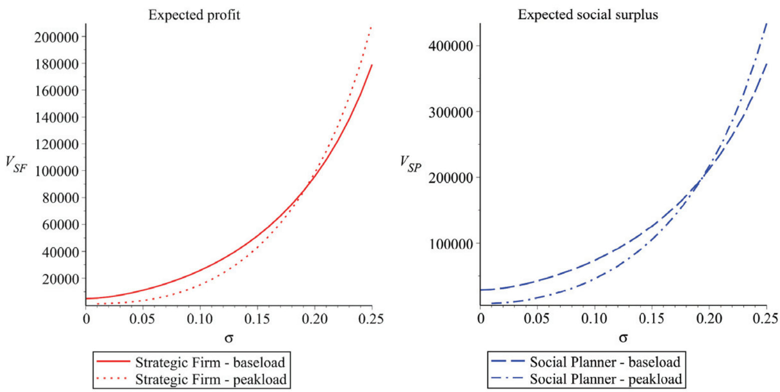

Figure 7: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For $A = 0.5$, $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 1$).*

Figure 7 shows how the expected discounted profits change for the strategic firm and the expected social surplus changes for the social planner for $\lambda = 1$. We see that both the expected discounted profits and social surpluses for both technologies increase with uncertainty. Furthermore, for both the strategic firm and the social planner cases, relatively low levels of uncertainty result in an investment of baseload generation but relatively high levels of uncertainty result in an investment of peakload generation. Straightforward justification of this finding is relatively low levels of σ makes the need for suspendible production less likely. However as σ increases, the possibility of the need for suspendible production makes the peakload investment preferable.

We also see that an increase in σ increases the expected profit and the expected social surplus exponentially. Furthermore we note that for lower levels of λ, and therefore higher investment capacity and lower demand trigger, the peakload generator benefits more from increasing uncertainty than the baseload generator. This effect has a larger impact for lower λ levels and makes the investor change preferences from one technology to another for low uncertainty.

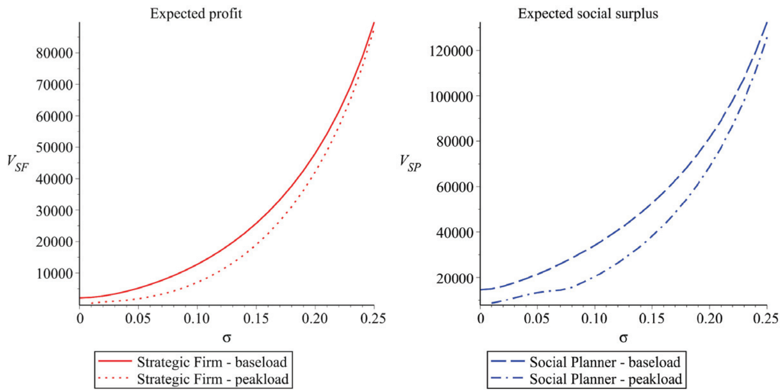

Figure 8: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For $A = 0.5$, $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 2$).*

Figure 8 gives the same plots for the $\lambda = 2$ case. We see that for the corresponding range of the uncertainty, investing in baseload generation returns higher expected profits for the strategic firm and higher expected social surplus for the social planner. Therefore for these cases, baseload technology will always be the choice of technology when the investment takes place. This result is mainly due to the value of λ. As we have mentioned previously, choice of peakload generation results in higher capacity investment, higher investment cost and higher production costs. Specifically the investment cost increases significantly for high levels of λ. And for the case in **Figure 8**, this negative impact exceeds the benefits of having a peakload generator. As a result, we do not see the peakload generation providing higher returns for either the strategic firm or the social planner.[7]

4 Conclusion

In this paper, we compare the investment timing and investment capacity for the optimal level of investment for a strategic firm and a social planner that have a one-time opportunity to invest in two types of electricity generators. In our model, the one-time investment decision requires the determination of demand shock trigger level, choice of technology and level of optimal capacity. We specifically investigate how the investment triggers, optimal capacities and technology choices change with the changes to the investment cost function, demand uncertainty and the level of installed capacity in the market.

In the numerical results, we confirm that increasing uncertainty tends to delay the investment and increase the investment capacity for all the cases. We also find that the strategic firm tends to invest at a higher demand trigger level and lower capacity compared to the social planner for both the baseload and peakload investment cases. Hence, the strategic firm is expected to invest at a later date while incurring lower investment costs. We additionally find that highly convex investment cost greatly diminishes the effect of market power on the investment decisions. Furthermore, we show that increased share of production in the market for the strategic firm does not necessarily increase its expected profits.

Further investigation of the expected profits for the strategic firm and the expected social surplus for the social planner reveals that, expected profits for the strategic firm almost always decrease with the level of installed capacity, whereas expected social surplus for the social planner exhibits an increase prior to declining due to high levels of installed capacity. The overview of the expected returns, for both the strategic firm and the social planner, further reveals that fixed baseload generation is preferable during low uncertainty cases whereas high uncertainty tends to result in the choice of flexible peakload generation.

[7] Note that we require $r - 2\alpha - \sigma^2 > 0$ to have a finite value for the investment project. In our numerical analysis, we have $\sigma \leq \sqrt{r - 2\alpha} \approx 0.2828$. See also Dangl (1999).

A Appendix

A.1 Proof of Proposition 1

In the proof of this Proposition, we use the same approach as Dangl (1999), Hagspiel *et al.* (2010) and Huisman and Kort (2012) by finding the first order condition for the value function with respect to K_{SF}.[8]

$$\frac{\partial}{\partial K_{SF}}\left[\frac{AK + K^*_{SF}}{r-\alpha}X - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_B)K^*_{SF}}{r} - \frac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda})\right] = 0 \quad (51)$$

where the maximality of the solutions are provided by checking that the second order derivate for corresponding solutions is less than zero.

Furthermore, **(18)** is found by using value matching and smooth pasting conditions from **(16)**. Namely,

$$B{X^*_{SF}}^{\beta} + \frac{AK}{r-\alpha}X^*_{SF} - \frac{(\gamma K + c)AK}{r} = \frac{AK + K^*_{SF}}{r-\alpha}X^*_{SF} - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_B)K^*_{SF}}{r} - \frac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda}) \quad (52)$$

$$\beta B{X^*_{SF}}^{\beta-1} + \frac{AK}{r-\alpha} = \frac{AK + K^*_{SF}}{r-\alpha} \quad (53)$$

Combining these two equations implicitly gives X^*_{SF} as,

$$\frac{\beta-1}{\beta}\frac{K^*_{SF}}{r-\alpha}X^*_{SF} - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_B)K^*_{SF}}{r} - I - {K^*_{SF}}^{\lambda} = 0 \quad (54)$$

Note that, these equations are only sufficient conditions and the equations may have multiple solutions that does not necessarily give the same expected value since we can not derive a straightforward second order condition for **(51)**. But the propositions in this paper make it possible to determine a

[8] As the value-matching condition **(52)** suggests, maximizing the value function at $X = {X_{SF}}^*$ maximizes the option value to invest at the same point.

finite number of candidates, where the optimal solution returns the highest expected value for the total assets.

A.2 Proof of Proposition 2

As before, the value function before the time of new peakload investment is given by:

$$V(X) = \begin{cases} LX^{\beta_1} + \dfrac{AK}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} & \text{if } X < X^*_{SF} \\ DX^{\beta_2} + \dfrac{AK + K^*_{SF}}{r-\alpha}X - \dfrac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda}) & \text{if } X = X^*_{SF} \\ -\dfrac{(\gamma(A+1)K + \gamma K^*_{SF} + c_P)K^*_{SF}}{r} & \end{cases}$$

where X^*_{SF} is the trigger demand shock level that the investment in new peakload capacity takes place, DX^{β_2} is the option value to suspend operation and LX^{β_1} is the option value to invest. Furthermore, $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{55}$$

(28) is found by deriving the value function at the time of investment with respect to K_{SF}. So, we evaluate;

$$\frac{\partial}{\partial K_{SF}}\left[D(K_{SF}){X^*_{SF}}^{\beta_2} + \frac{AK + K^*_{SF}}{r-\alpha}X^*_{SF} - \frac{(\gamma(A+1)K + \gamma K^*_{SF} + c_P)K^*_{SF}}{r} - \frac{(\gamma K + c)AK}{r} - (I + {K^*_{SF}}^{\lambda})\right] = 0 \tag{56}$$

where the maximality of the solutions are provided by checking that the second order derivate for corresponding solutions is less than zero.

(29) is found by using value matching and smooth pasting conditions from the value function before the investment **(27)**. Hence,

$$\begin{aligned} L{X_{SF}^*}^{\beta_1} &+ \frac{AK}{r-\alpha}X_{SF}^* - \frac{(\gamma K + c)AK}{r} = D{X_{SF}^*}^{\beta_2} + \frac{AK + K_{SF}^*}{r-\alpha}X_{SF}^* \\ &- \frac{(\gamma(A+1)K + \gamma K_{SF}^* + c_P)K_{SF}^*}{r} - \frac{(\gamma K + c)AK}{r} - (I + {K_{SF}^*}^{\lambda}) \end{aligned} \quad (57)$$

$$\beta_1 L{X_{SF}^*}^{\beta_1 - 1} + \frac{AK}{r-\alpha} = \beta_2 D{X_{SF}^*}^{\beta_2 - 1} + \frac{AK + K_{SF}^*}{r-\alpha} \quad (58)$$

Furthermore, constants C and D are found by using value matching and smooth pasting conditions from the value function after the investment, **(25)**. Hence,

$$\begin{aligned} C{\underline{X}_{SF}}^{\beta_1} &+ \frac{AK}{r-\alpha}\underline{X}_{SF} - \frac{(\gamma K + c)AK}{r} = D{\underline{X}_{SF}}^{\beta_2} + \frac{AK + K_{SF}^*}{r-\alpha}\underline{X}_{SF} \\ &- \frac{(\gamma(A+1)K + \gamma K_{SF}^* + c_P)K_{SF}^*}{r} - \frac{(\gamma K + c)AK}{r} \end{aligned} \quad (59)$$

$$\beta_1 C{\underline{X}_{SF}}^{\beta_1 - 1} + \frac{AK}{r-\alpha} = \beta_2 D{\underline{X}_{SF}}^{\beta_2 - 1} + \frac{AK + K_{SF}^*}{r-\alpha} \quad (60)$$

Combining these two equations implicitly gives:

$$C = \frac{(\gamma(A+1)K + \gamma K_{SF}^* + c_P)K_{SF}^*}{r}\frac{\beta_2}{\beta_2 - \beta_1}{\underline{X}_{SF}}^{-\beta_1} + \frac{1-\beta_2}{\beta_2 - \beta_1}\frac{K_{SF}^*}{r-\alpha}\underline{X}_{SF}^{1-\beta_1} \quad (61)$$

$$D = \frac{(\gamma(A+1)K + \gamma K_{SF}^* + c_P)K_{SF}^*}{r}\frac{\beta_1}{\beta_1 - \beta_2}{\underline{X}_{SF}}^{-\beta_2} + \frac{1-\beta_1}{\beta_1 - \beta_2}\frac{K_{SF}^*}{r-\alpha}\underline{X}_{SF}^{1-\beta_2} \quad (62)$$

The parameters C, D, and D' can be simplified by using the following expressions:

$$\underline{X}_{SF} = \gamma(A+1)K + \gamma K_{SF} + c_P \quad \text{and} \quad \frac{\beta_1\beta_2}{(\beta_2 - 1)(\beta_1 - 1)} = \frac{r}{r-\alpha} \quad (63)$$

Therefore, we have:

$$C = \frac{\beta_2}{(\beta_1 - \beta_2)(\beta_1 - 1)}\frac{K_{SF}^*}{r}\underline{X}_{SF}^{1-\beta_1} \quad (64)$$

$$D = \frac{\beta_1}{(\beta_2 - \beta_1)(\beta_2 - 1)} \frac{K^*_{SF}}{r} \underline{X}^{1-\beta_2}_{SF} \tag{65}$$

$$D'(K^*_{SF}) = \frac{\beta_1}{(\beta_2 - \beta_1)(\beta_2 - 1)} \frac{1}{r} \underline{X}^{1-\beta_2}_{SF} - \frac{\gamma \beta_1}{\beta_2 - \beta_1} \frac{K^*_{SF}}{r} \underline{X}^{-\beta_2}_{SF} \tag{66}$$

A.3 Proof of Proposition 3

In the proof of this Proposition, we use the same approach as **Proposition 1** by finding the first order condition for the value function with respect to K_{SP}.

$$\frac{\partial}{\partial K_{SP}} \left[\frac{K + K^*_{SP}}{r - \alpha} X - \frac{\gamma (K + K^*_{SP})^2 + 2cK + 2c_B K^*_{SP}}{2r} - (I + {K^*_{SP}}^{\lambda}) \right] = 0 \tag{67}$$

where the maximality of the solutions are provided by checking that the second order derivate for corresponding solutions is less than zero.

Furthermore, **(43)** is found by using value matching and smooth pasting conditions from **(40)**. Namely,

$$\begin{aligned} G{X^*_{SP}}^{\beta} &+ \frac{K}{r - \alpha} X^*_{SP} - \frac{\gamma K^2 + 2cK}{2r} = \frac{K + K_{SP}}{r - \alpha} X^*_{SP} - (I + {K^*_{SP}}^{\lambda}) \\ &- \frac{\gamma (K + K_{SP})^2 + 2cK + 2c_B K_{SP}}{2r} \end{aligned} \tag{68}$$

$$\beta G {X^*_{SP}}^{\beta - 1} + \frac{K}{r - \alpha} = \frac{K + K^*_{SP}}{r - \alpha} \tag{69}$$

Combining these two equations implicitly gives X^*_{SP} as,

$$\frac{\beta - 1}{\beta} \frac{K^*_{SP} X^*_{SP}}{r - \alpha} - \frac{(2\gamma K + \gamma K_{SP} + 2c_B) K^*_{SP}}{2r} - I - {K^*_{SP}}^{\lambda} = 0 \tag{70}$$

A.4 Proof of Proposition 4

As before, the value function before the time of new peakload investment is given by:

$$W(X) = \begin{cases} MX^{\beta_1} + \dfrac{K}{r-\alpha}X - \dfrac{\gamma K^2 + 2cK}{2r} & \text{if } X < X^*_{SP} \\ JX^{\beta_2} + \dfrac{K+K_{SP}}{r-\alpha}X - \dfrac{\gamma K^2 + 2cK}{2r} - (I + {K^*_{SP}}^{\lambda}) & \text{if } X = X^*_{SP} \\ -\dfrac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r} & \end{cases}$$

where X^*_{SP} is the trigger demand shock level that the investment in new peakload capacity takes place, JX^{β_2} is the option value to suspend operation and MX^{β_1} is the option value to invest. Furthermore, $\beta_1 > 1$ and $\beta_2 < 0$ are the roots of the quadratic equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0. \tag{71}$$

(49) is found by deriving the value function at the time of investment with respect to K_{SP}. So, we evaluate;

$$\begin{aligned} \frac{\partial}{\partial K_{SF}} \Bigg[J(K_{SP}){X^*_{SP}}^{\beta_2} + \frac{K+K_{SP}}{r-\alpha}X^*_{SP} - \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r} \\ -\frac{\gamma K^2 + 2cK}{2r} - (I + {K^*_{SP}}^{\lambda}) \Bigg] = 0 \end{aligned} \tag{72}$$

where the maximality of the solutions are provided by checking that the second order derivate for corresponding solutions is less than zero.

(50) is found by using value matching and smooth pasting conditions from the value function before the investment **(48)**. Namely,

$$\begin{aligned} M{X^*_{SP}}^{\beta_1} &+ \frac{K}{r-\alpha}X^*_{SP} - \frac{\gamma K^2 + 2cK}{2r} = J{X^*_{SP}}^{\beta_2} + \frac{K+K_{SP}}{r-\alpha}X^*_{SP} \\ &- \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r} - \frac{\gamma K^2 + 2cK}{2r} - (I + {K^*_{SP}}^{\lambda}) \end{aligned} \tag{73}$$

$$\beta_1 M {X^*_{SP}}^{\beta_1 - 1} + \frac{K}{r-\alpha} = \beta_2 D {X^*_{SP}}^{\beta_2 - 1} + \frac{K + K^*_{SF}}{r-\alpha} \tag{74}$$

Furthermore, constants J and H are found by using value matching and smooth pasting conditions from **(44)**. Hence,

$$\begin{aligned} M{\underline{X}_{SP}}^{\beta_1} &+ \frac{K}{r-\alpha}\underline{X}_{SP} - \frac{\gamma K^2 + 2cK}{2r} = J{\underline{X}_{SP}}^{\beta_2} + \frac{K + K_{SP}}{r-\alpha}\underline{X}_{SP} \\ &- \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r} - \frac{\gamma K^2 + 2cK}{2r} \end{aligned} \tag{75}$$

$$\beta_1 M {\underline{X}_{SP}}^{\beta_1 - 1} + \frac{K}{r-\alpha} = \beta_2 J {\underline{X}_{SP}}^{\beta_2 - 1} + \frac{K + K^*_{SP}}{r-\alpha} \tag{76}$$

Combining these two equations implicitly gives:

$$J = \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r}\frac{\beta_1}{\beta_1 - \beta_2}{\underline{X}_{SP}}^{-\beta_2} + \frac{1-\beta_1}{\beta_1 - \beta_2}\frac{K^*_{SP}}{r-\alpha}\underline{X}_{SP}^{1-\beta_2} \tag{77}$$

$$H = \frac{(\gamma K^*_{SP} + 2\gamma K + 2c_P)K^*_{SP}}{2r}\frac{\beta_2}{\beta_2 - \beta_1}{\underline{X}_{SP}}^{-\beta_1} + \frac{1-\beta_2}{\beta_2 - \beta_1}\frac{K^*_{SP}}{r-\alpha}\underline{X}_{SP}^{1-\beta_1} \tag{78}$$

The parameters H, J, and J' can be simplified by using the following expressions:

$$\underline{X}_{SP} = \gamma K + c_P + \frac{\gamma}{2}K_{SP} \text{ and } \frac{\beta_1 \beta_2}{(\beta_2 - 1)(\beta_1 - 1)} = \frac{r}{r-\alpha} \tag{79}$$

Therefore, we have:

$$H = \frac{\beta_2}{(\beta_1 - \beta_2)(\beta_1 - 1)}\frac{K^*_{SP}}{r}\underline{X}_{SP}^{1-\beta_1} \tag{80}$$

$$J = \frac{\beta_1}{(\beta_2 - \beta_1)(\beta_2 - 1)}\frac{K^*_{SP}}{r}\underline{X}_{SP}^{1-\beta_2} \tag{81}$$

$$J'(K^*_{SP}) = \frac{\beta_1}{(\beta_2 - \beta_1)(\beta_2 - 1)}\frac{1}{r}\underline{X}_{SP}^{1-\beta_2} - \frac{\gamma}{2}\frac{\beta_1}{\beta_2 - \beta_1}\frac{K^*_{SP}}{r}\underline{X}_{SP}^{-\beta_2} \tag{82}$$

A.5 Additional Figures

A.5.1 Impact of Cost Function

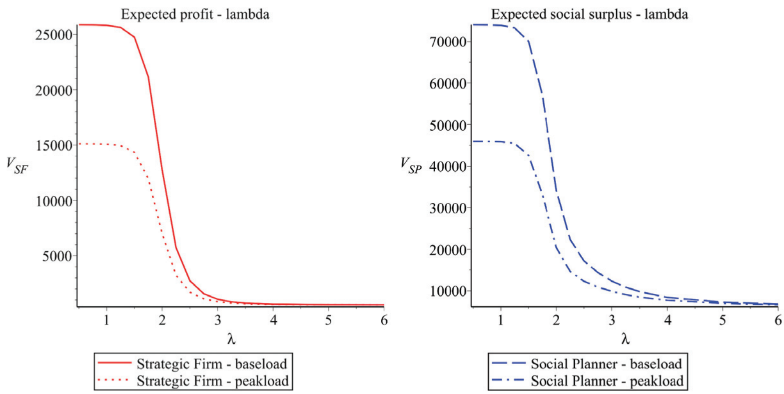

Figure 9: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner based on* λ *(For* $A = 0.5$*,* $K = 100$*,* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\sigma = 0.1$ *and* $\gamma = 0.1$*).*

A.5.2 Impact of Uncertainty

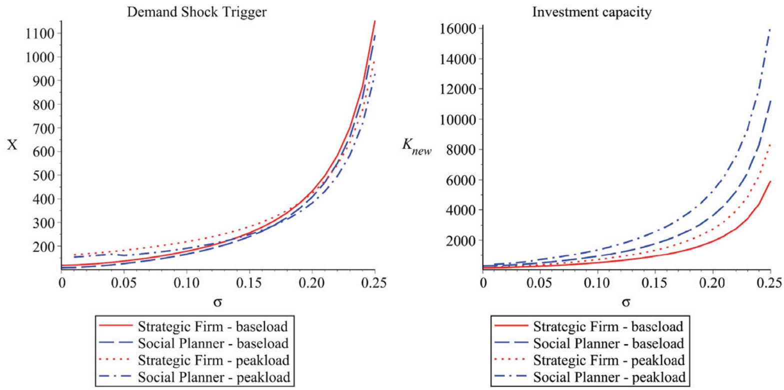

Figure 10: *Investment Triggers and Capacities based on uncertainty (For* $A = 0.5$*,* $K = 100$*,* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\gamma = 0.1$ *and* $\lambda = 1$*).*

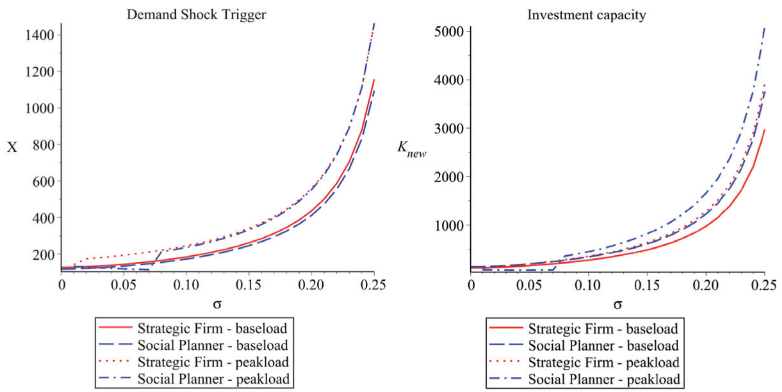

Figure 11: *Investment Triggers and Capacities based on uncertainty (For* $A = 0.5$*,* $K = 100$*,* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\gamma = 0.1$ *and* $\lambda = 2$*).*

A.5.3 Impact of Installed Capacity

- For $\lambda = 0.5$:

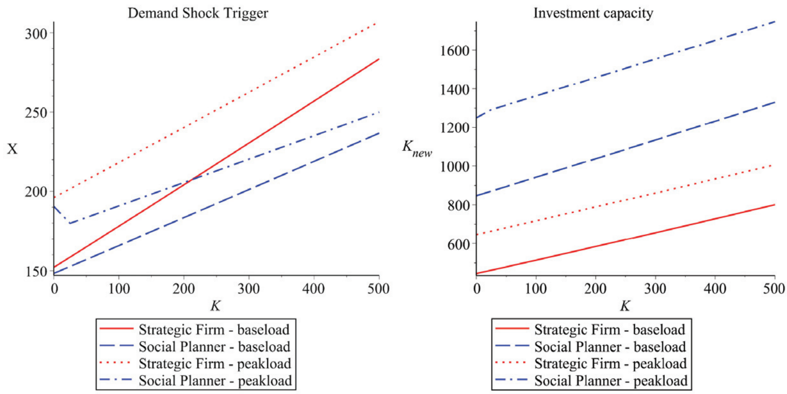

Figure 12: *Investment Triggers and Capacities based on installed capacity (For $A = 0.5$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 0.5$).*

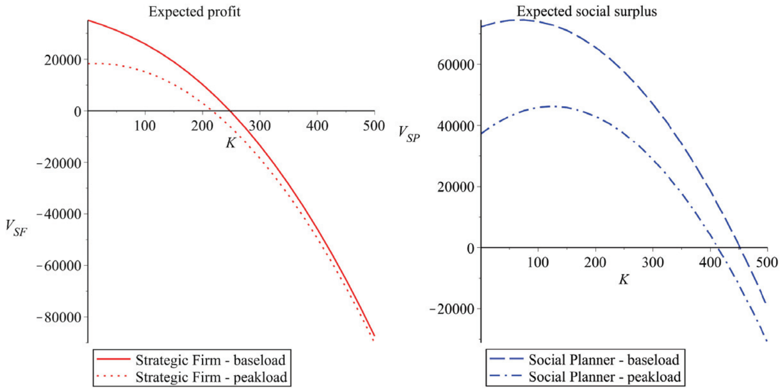

Figure 13: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For $A = 0.5$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 0.5$).*

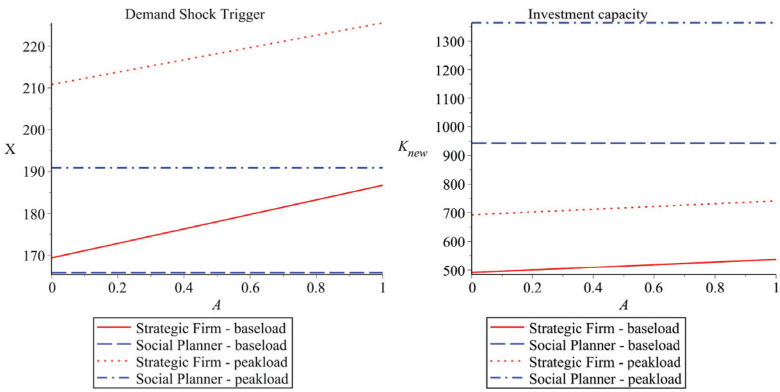

Figure 14: *Investment Triggers and Capacities based on installed capacity based on A (For $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ and $\lambda = 0.5$).*

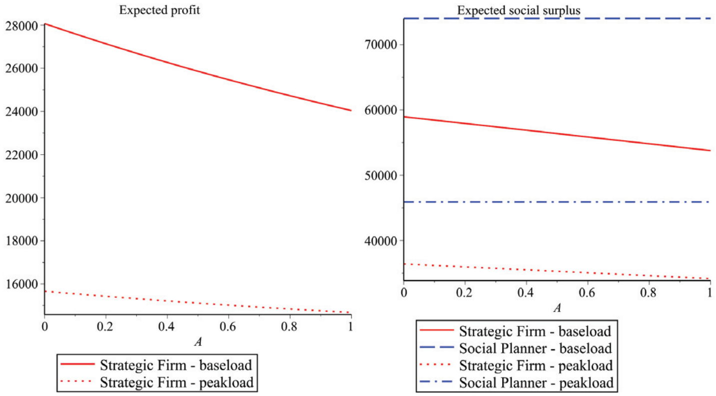

Figure 15: *Expected Profit and Social Surplus for the Strategic Firm (For* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\sigma = 0.1$*,* $\gamma = 0.1$ *and* $\lambda = 0.5$*).*

- For $\lambda = 1$:

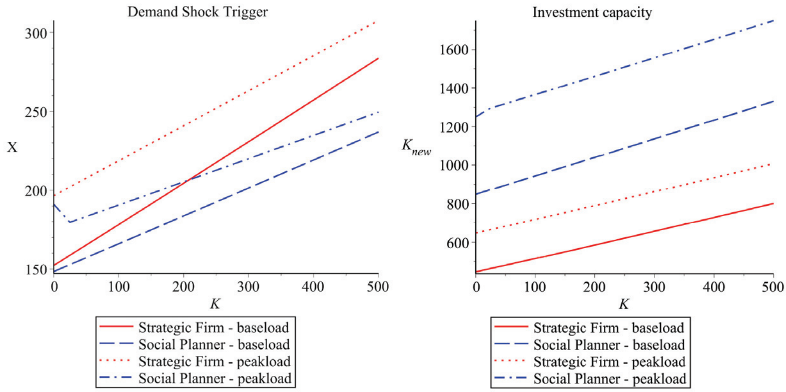

Figure 16: *Investment Triggers and Capacities based on installed capacity (For* $A = 0.5,\ I = 10000,\ c_B = 80,\ c = 100\ c_P = 120\ r = 0.1,\ \alpha = 0.01,\ \sigma = 0.1,\ \gamma = 0.1$ *and* $\lambda = 1$*).*

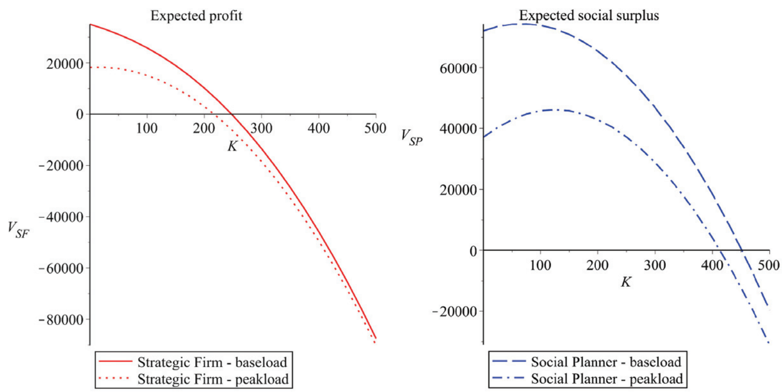

Figure 17: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For* $A = 0.5,\ I = 10000,\ c_B = 80,\ c = 100\ c_P = 120\ r = 0.1,\ \alpha = 0.01,\ \sigma = 0.1,\ \gamma = 0.1$ *and* $\lambda = 1$*).*

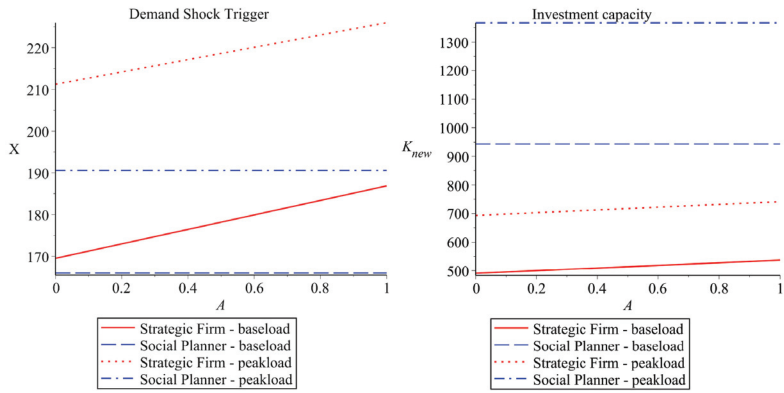

Figure 18: *Investment Triggers and Capacities based on installed capacity based on* A *(For* $K = 100$, $I = 10000$, $c_B = 80$, $c = 100$ $c_P = 120$ $r = 0.1$, $\alpha = 0.01$, $\sigma = 0.1$, $\gamma = 0.1$ *and* $\lambda = 1$*).*

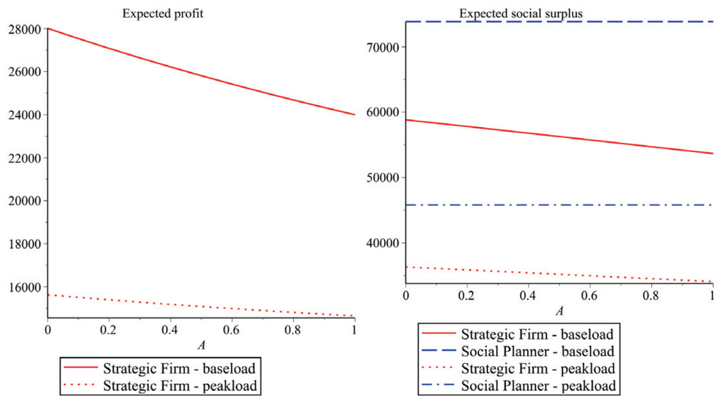

Figure 19: *Expected Profit and Social Surplus for the Strategic Firm (For* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\sigma = 0.1$*,* $\gamma = 0.1$ *and* $\lambda = 1$*).*

A.5.4 Technology Choice

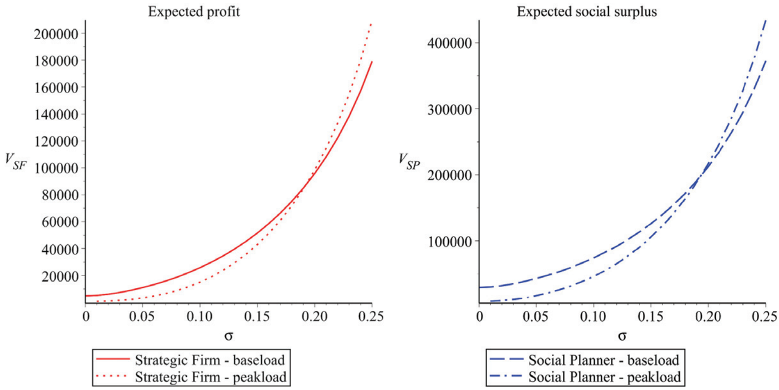

Figure 20: *Expected Profit for the Strategic Firm and Social Surplus for the Social Planner (For* $A = 0.5$*,* $K = 100$*,* $I = 10000$*,* $c_B = 80$*,* $c = 100$ $c_P = 120$ $r = 0.1$*,* $\alpha = 0.01$*,* $\sigma = 0.1$*,* $\gamma = 0.1$ *and* $\lambda = 0.5$*).*

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Conclusion

This dissertation presents three chapters that deals with the short and long term impacts of market power in the electricity markets. The dissertation primarily adopts a real options approach to analyze the short and long term decisions that are at least partially irreversible. The main contribution of the dissertation is to investigate the effects of market power when the strategic producers own a portfolio of generation technologies and have ability to affect prices while facing demand or production uncertainties.

The first chapter studies the effects of operational characteristics of power plants on optimal dispatch decisions and estimation of market power. Specifically, I give a real options model to show how operational characteristics of power plants and market uncertainty affect start up and shut down decisions. Furthermore, I derive start up and shut down trigger levels of the peakload generator for both monopoly and social planner cases. These trigger levels are obtained numerically due to the nature of the real options model.

I show that in the case of ownership of multiple generation technologies, optimal dispatch decisions cause capacity withholding for the peakload generator in both the monopoly and the social planner cases. Due to higher start up and shut down trigger levels, the monopolist is expected to keep the peakload generator active for a significantly shorter period of time compared to the social planner. Moreover, the difference between the start up trigger prices for the social planner and the marginal cost reveals significant levels of *real options premium*. Under the existence of start up and shut down costs, the real options premium takes values of more than 30% of the marginal cost of the peakload generator. Additionally, for both fixed and flexible peakload generation cases, the real options premium explains about 24% to 30% of the monopolists mark-up. Furthermore, the real options-adjusted Lerner Index shows that an increase in start up trigger prices does not necessarily mean an increase in the extent of market power of the monopolist.

The second chapter investigates the short term effects of wind generator ownership by the owners of fossil-fueled peakload generators. I provide a Cournot oligopoly model to show the effects on the individual and total peakload production levels as well as the market price.

Theoretical derivations in this chapter show that wind generator ownership results in significantly lower total peakload production and higher market price. Moreover, every peakload firm is influenced by the aggregate wind generator ownership. In that regard, while the firms without wind generators increase their peakload production, the firms with wind generators decrease theirs. Furthermore, by internalizing their share of wind generation, peakload firms decrease their total production costs and earn higher profits. In addition, when all wind generators are owned by the peakload firms, the impact of wind generation on the market outcomes vanishes. I further find that the peakload firms that own wind generators ask higher start up and shut down prices under higher levels of wind generator ownership. I additionally show that the effect of the volatility of the wind generation on the expected consumer, producer and total social surpluses decreases with the aggregate wind generation ownership due to internalization of the wind generation. Finally, further analysis documents that a *feed-in premium* support scheme does not affect the peakload firms production levels and hence the market outcomes. However, there is an increase in the total production and a decrease in the market price under a *feed-in tariff* type of support scheme.

The third chapter compares the investment timing and the optimal level of investment for a hypothetical monopolist and a social planner that have a one-time opportunity to invest in a generator with either fixed or flexible production. It specifically investigates how the investment triggers, optimal capacities and technology choices change with the changes to the investment cost function, demand uncertainty and the level of installed capacity in the market.

In the numerical results, we confirm that increasing uncertainty tends to delay the investment and increase the investment capacity for all the cases. We also find that the strategic firm tends to invest at a higher demand trigger level and lower capacity compared to the social planner for both the baseload and peakload investment cases. Hence, the strategic firm is expected to invest at a later date while incurring lower investment costs. We additionally find that highly convex investment cost greatly diminishes the effect of market power on the investment decisions. We also find that with increased levels of installed capacity and installed capacity ownership, the strategic firm delays the new investment and increases the new investment capacity. Furthermore, we show that increased share of production in the market for the strategic firm does not necessarily increase its expected profits.

Further investigation of the expected profits for the strategic firm and the expected social surplus for the social planner reveals that, expected profits for the strategic firm tends to decrease with the level of installed capacity, whereas expected social surplus for the social planner exhibits an increase prior to declining due to high levels of installed capacity. The overview of the expected returns, for both the strategic firm and the social planner, further reveals that fixed baseload generation is preferable during low uncertainty cases whereas high uncertainty tends to result in the choice of flexible peak-load generation.

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