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Diplom-Mathematiker Raimund Malischek

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Referent:	Prof. Dr. Felix Höffler
Korreferent:	PD Dr. Dietmar Lindenberger
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Chapter 1

Introduction

Energy economics is a broad field offering the researcher opportunities to explore different research questions that are inspired by real world energy systems including electricity and resource markets and related environmental and climate issues. In this thesis, the following four essays on energy economics, covering the above listed topics, are presented:

- Chapter 2: A test of the theory of nonrenewable resources - Controlling for market power and exploration (based on Malischek and Tode, 2015)
- Chapter 3: Models of endogenous production capacity investment in spatial oligopolistic markets
- Chapter 4: Modeling strategic investment decisions in spatial markets (based on Lorenczik et al., 2014)
- Chapter 5: The future of nuclear power in France: an analysis of the costs of phasing-out (based on Malischek and Trüby, 2014).

The essays are stand alone and may be read in any order. The selection of research topics and methodologies presented in these essays is governed by the author's interests, the hope that by probing these markets new knowledge and understanding could be gained, as well as by the adequacy of the methodologies to the respective topics.

This introduction provides a short summary of the four essays, including a discussion of how each essay adds to existing literature and improves understanding of the topics explored. The introduction concludes with reflections on future research and possible improvements to methodologies for each of the four essays.

1.1 Introducing the essays

Chapter 2 investigates one of the workhorse models of resource economics, the Hotelling model of an inter-temporally optimizing resource extracting firm. The essay is based on Malischek and Tode (2015) to which both authors contributed in equal parts. It is motivated by recently sparked interest in Hoteling's model as a result of new applications like Hans-Werner Sinn's Green Paradox and the fact that, despite providing a convincing theory of fundamental concepts like resource scarcity, empirical validations of the Hotelling model are largely absent. This is usually attributed to data shortcomings in the empirical analyses conducted so far or the simplifying assumptions made in the baseline Hotelling model. Even though further work has therefore focused on theoretical extensions of the standard Hotelling model, convincing empirical evidence for the theory is still missing. The empirical analysis presented in Chapter 2 adds to the literature on tests of the Hotelling model by extending the standard Hotelling model by exploration activity as presented in Pindyck (1978) and market power as presented in Ellis and Halvorsen (2002) and bringing this extended model, which is in essence a combination of existing model extensions, to a newly constructed data set for the uranium mining industry. Applying a Hausman test, we test whether a major resource extracting mining firm in the industry is following the theory's predictions. Our results show that the theory is rejected in all considered settings. We therefore add to the existing literature on negative results of the theory's validity.

Chapters 3 and 4 turn to a different research stream in energy economics which is not restricted to energy market applications but also draws on game theory and operations research. The essays presented in the two chapters investigate the difference in market outcomes under spot-market based trade as compared to long-term contract based trade in oligopolistic markets with investments. The analysis is motivated by recent developments in resource markets, including the iron ore and the metallurgical coal markets, which are experiencing a shift away from long-term contract-based trade towards spot-market based trade. It is also relevant for electricity markets, which feature a mix of differently traded products.

Chapter 3 analyzes the electricity market application of the impact of a shift away from long-term contracts to spot-market based trading on supply, investment and welfare. It takes an analytical approach and presents a spatial extension of the one node, peak and base-load player model presented in Murphy and Smeers (2005). The extended model consists of two markets and two players, representing a peak and a base-load producer, which can each serve both markets. In the chapter, criteria are developed for the two market structures to result in the same market outcome. Further, it is shown that, if divergent and under certain assumptions, supply, investments and consumer welfare are higher under spot-market based trade than under long-term contracts.

Chapter 4 changes both methodology and market focus of the investigation, moving from an analytical to an empirical analysis and from a simple electricity market model to a detailed model of the global seaborne metallurgical coal market. The chapter is based on Lorenczik et al. (2014) to which all three authors contributed in equal parts. It presents for the first time the empirical solution of a large-scale spatial oligopolistic spot-market based trade model with investments. The model drops the rather restrictive assumptions posed on the number of players and their cost structures used in Chapter 3. The validity of the developed modeling approach is shown through various sensitivity analyses. The results demonstrate in this more general context that supply, investments and welfare are higher under spot-market based trade than under long-term contracts.

Chapter 5 investigates investment decisions in yet a different light than Chapters 3 and 4, namely by looking at the influence of uncertainty on investment decisions. It is based on Malischek and Trüby (2014) to which both authors contributed in equal parts. While previous work in this area of energy economics has mostly focused on weather or fuel-price uncertainty, Chapter 5 focuses on the effect of policy uncertainty on market outcomes. The topic is motivated by the central role policy frameworks play in energy markets, in particular in electricity markets. This assertion is best illustrated by the German and European electricity markets which are both strongly influenced by numerous quotas, remuneration schemes and policy decisions against/in favor of certain technologies. Further, the rapid speed at which policies may change poses a significant amount of uncertainty to market participants. The recent history of German nuclear policy after the Fukushima catastrophe, leading to the phase-out decision from the technology just shortly after prolonged lifetimes of nuclear power plants had been decided on, may serve as an illustration. In Chapter 5, we turn our attention to the largest nuclear power producer in Europe, France. With France heatedly debating the role of nuclear technology, we analyze how policy uncertainty regarding nuclear power in France may feature in the French and European power sector. Different pathways for nuclear policy in France are investigated using a stochastic linear programing model of the European power system. The analysis shows that the costs of uncertainty in this particular application are rather low compared to the overall costs of a nuclear phase-out.

1.2 Future research and possible improvements to methodologies

The four chapters address different research questions, each of which requires a different methodology. Chapter 2 presents a quantitative analysis of an extended Hotelling model. For this analysis, econometric methods are applied. Even though the baseline Hotelling model is extended by the features of market power and exploration activity, the theory could not be validated. The critique applied to previous literature may therefore also apply to the analysis presented here: First, the model may fail to incorporate important features of the industry or of the decision-making process within the firm. One such factor that industry participants might consider and which is not considered in the model is uncertainty. For example, in the essay, despite uranium demand being rather well predictable due to long lead times of nuclear power plant constructions and the predictability of nuclear power plant shut downs, the events following the nuclear accident at Fukushima show that uranium demand is subject to shocks and uncertainty. A test for this particular shock is provided in the appendix to the chapter. The test shows that the findings of the analysis do not not change by accounting for this shock. A more in-depth analysis of shocks and an extension of the model to incorporate uncertainty may, however, provide an interesting stream for further research, in particular in light of testing other markets. Second, the data collected may be insufficient to capture the firm's behavior in all detail. In response to this critique it may be noted that the collected data are the best available to the authors and the particular choices and assumptions made are documented in the appendix to the chapter.

In Chapters 3 and 4, strategic interaction of players in a game theory context is introduced. While it is possible to derive analytically properties of a simple version of the model in Chapter 3, the complexity of the model due to the large number of players in Chapter 4 makes an analytical solution infeasible and therefore requires an empirical analysis and computer assistance. Several extensions of the analysis presented in the two chapters might be of interest. First, the restrictions imposed in Chapter 3 on the players' cost structure may be too restrictive to apply to the important class of resource-market applications. While the electricity-market application introduced in Chapter 3 is important, further research could investigate more general cost structures and explore whether the results may be extended to a more general context. Second, only one supply and one investment period are considered in the models in Chapter 4. As investments usually have a medium to longer-term horizon, taking into account several supply and investment periods might be more adequate. However, rapidly increasing computer run-time when using more periods prohibited such an analysis. Third, investment decisions are typically prone to uncertainty regarding certain parameters, like for instance demand.

As with the issue of multiple time periods mentioned above, this analysis has not been within the scope of the current modeling and computational power.

Chapter 5 uses a stochastic linear programing model of the European power system to investigate the effect of policy uncertainty on system costs. Probably the most important critique to the analysis presented in Chapter 5 is that there are costs that are *not* considered in the analysis. These costs include among others the costs of nuclear catastrophes, the risk of operating nuclear plants and the costs of storing nuclear waste. These costs are at best hard, if not to say, impossible to quantify. In order to keep the analysis within the boundaries of the modeling approach taken and in order not to get lost in discussions on the quantification of these costs, these costs are not included in the analysis. Further, retrofit and investment costs for nuclear power plants can only be approximated and are based on publicly-available resources. Clearly these costs are prone to uncertainty and there is a large bandwidth of costs that could be considered reasonable. Extending the work presented in Chapter 5 through various further sensitivity analyses may be a promising avenue for future research.

Chapter 2

A test of the theory of nonrenewable resources - Controlling for market power and exploration

Despite the central role of the Hotelling model within the theory of nonrenewable resources, tests of the model are rarely found. If existent, these tests tend to ignore two key features, namely market power and exploration. We therefore extend the literature on tests of Hotelling's theory by conducting an implicit price behavior test, incorporating for the first time the concepts of market power and exploration into a single model. When applied to a newly constructed data set for the uranium mining industry, the null hypothesis of the firm optimizing inter-temporally as implied by Hotelling's theory is rejected in all settings. However, parameter estimates of the model still yield valuable information on cost structure, resource scarcity and market power. Our results suggest that the shadow price of the resource in situ is comparably small at the beginning of the observations and is therefore potentially overshadowed by market power. However, even as the shadow price increases over time, firms still fail to incorporate it in their decision making.

2.1 Introduction

There is hardly a field in economics that has been influenced by one single publication as much as the field of resource economics. Harold Hotelling published his work on the economics of exhaustible resources in 1931 (Hotelling, 1931). The paper gained attention in the 1970s due to the oil embargo and the subsequent energy crisis as well as the debate initiated by Meadows et al. (1972). Even today, the assumption of inter-temporal optimization within the nonrenewable resource industry, as introduced by Hotelling, is the foundation for many policy recommendations as seen in Hans-Werner Sinn's green paradox (Sinn, 2008).

Even though Hotelling's theory maintained academic attention for over 80 years, empirical applications and tests of the theory are rarely found mainly due to the vast number of influencing factors within the model paired with the unavailability of appropriate data sets. However, in order to derive policy recommendations, such as the ones implied by the green paradox, understanding the significance of the theory is crucial. Thus, the question as to whether the scarcity of a nonrenewable resource influences the actual decision-making process of a mining industry is the focus of this analysis.

This process depends on the value of the resource in situ (which can be represented by the shadow price, the scarcity rent or the user cost) and whether it is large enough to be incorporated into the firm's choice of variables. The relative size of the shadow price of the resource in situ compared to the full cost of production crucially depends on different characteristics of the extraction and processing of the resource as well as the market in which the firm is operating.

So far, the majority of empirical tests addressed methodological or data issues and hardly found evidence of the practical relevance of Hotelling's theory. Yet, two factors are mostly ignored that directly influence the shadow price and a firm's decisions. First, the resource shadow price depends not only on the extraction decisions but also on decisions made in order to increase the resource stock by exploratory activities. Exploration influences the shadow price as under the assumption that lower cost deposits will be produced first, increasing resource stock decreases extraction costs (Pindyck, 1978). For that reason, exploration is a critical feature of mining industries (Krautkraemer, 1998). Second, the market structure has impacts on a firm's decision regarding extraction. For instance, for a monopolistic producer of a nonrenewable resource, it might be optimal to restrict production in order to increase prices (Lasserre, 1991). Further, the existence of rents from market power might support a conjecture by Halvorsen (2008), namely that the shadow price of the resource in situ is too small to be considered in a firm's decisions. The existence of rents from market power might therefore overshadow shadow prices and hence, explain, why tests tend to reject the theory.

Given the relevance of market power and exploration in nonrenewable resource industries, we extend the literature on tests of Hotelling's theory by conducting a test based on the methodology introduced by Halvorsen and Smith (1991), incorporating for the first time the concepts of market power, as introduced by Ellis and Halvorsen (2002), and exploration, as in Pindyck (1978) into a single model. Using data from a newly constructed data set for the uranium mining industry, we study the consistency of the behavior of the shadow price with the Hotelling model and perform an implicit price behavior test for a major firm in the industry. We estimate two models: one accounting only for the static optimality implied by the Hotelling model and another accounting additionally for dynamic optimality. Applying a Hausman specification test, the null hypotheses of the firm extracting the resource inter-temporally optimal is rejected in all of the settings analyzed. Despite this rejection, parameter estimates of the model still allow us to derive information on costs, resource scarcity and market power mark-ups. These estimates suggest that the shadow price of the resource in situ is comparably small at the beginning of the observations and may be overshadowed by market power, which may explain why the firm fails to optimize inter-temporally. However, even as steep increases in shadow prices occur in the later observations, the firm still fails to incorporate its size into its decision making.

The remainder of this article is structured as follows: Section 2.2 presents existing literature on the topic. Section 2.3 describes the theoretical model, while Section 2.4 introduces the applied econometric framework. Section 2.5 introduces the data used and market considered. Test results and parameter estimates are discussed in Section 2.6. Section 2.7 concludes.

2.2 Literature Review

Hotelling (1931) was the first to introduce and solve the inter-temporal optimization problem in nonrenewable resource economics. As a consequence, the concept of the shadow price of the resource in situ was also established. Academic and public interest was low until the end of the second half of the last century when the publication of Meadows et al. (1972) and Solow's lecture on Hotelling's model (Solow, 1974) boosted interest in the theory of nonrenewable resource extraction. Subsequent additions to the literature are extensively surveyed by Krautkraemer (1998). Today, Hotelling's work is considered to be the foundation of resource economics and plays a significant role in the discussion on climate change and, e.g., in the discussion on the green-paradox (Sinn, 2008).

As academic interest rose, first tests of the theory were conducted. Different analyzes have since been done, which Chermak and Patrick (2002) classified into two main groups: price path and price behavior tests. Price path tests examine whether the price of a nonrenewable resource changes according to Hotelling's r-percent rule (i.e., whether the price increases at the rate of interest). None of the price path analyzes done by Barnett and Morse (2013), Smith (1979) and Slade (1982) could find evidence for the theory in actual data. However, these tests come with strong assumptions resulting from simplifications in Hotelling's model: First, technology is assumed to be constant over time and second, the relation of extraction costs to the resource base and marginal costs is not considered.

Price behavior tests incorporate the price path into the decision-making process of the extracting firm. Explicit price behavior tests assume a process that consists of extraction and direct selling of the nonrenewable resource. This implies that the extracted resource is not processed and therefore marginal costs are simply given by the extraction costs. The results of these analyzes are ambiguous: While Farrow (1985) and Young (1992) reject the theory, Stollery (1983) and Slade and Thille (1997) obtain positive results whereas Miller and Upton (1985) present mixed results. As Chermak and Patrick (2002) point out, even though the test approach is similar across analyzes, data handling and underlying assumptions vary strongly.

For most nonrenewable resources, processing of the resource is a necessary step (e.g., extraction of the mineral of interest from the ore) before the good can be sold. As the majority of mining firms can, in general, be considered vertically integrated (i.e., offering both mining and processing of the resource), explicit price behavior tests are not applicable to most nonrenewable industries. Implicit price behavior tests, on the other hand, take vertical integration into account. The results of previous analyzes considering implicit price behavior are again mixed. While Halvorsen and Smith (1991) reject the theory, Chermak and Patrick (2001)[1] obtain positive results. Caputo (2011) develops a nearly complete set of the testable implications of the Hotelling model; however, he finds that data inadequacies prevent testing all the implications of the theory. Compared to Caputo's analysis, the test in this paper could be considered to be only a partial test, as we closely follow the approach of Halvorsen and Smith (1991).

Table 2.1 gives an overview of the tests conducted thus far and their main characteristics.[2] It becomes obvious that the tests do not only vary in their testing approach but also in the data time resolution and level. Furthermore, almost all articles assume perfect competition in the input and output markets. Exploration activities as a means of increasing the resource base are generally not considered.

[1] Using data from Chermak and Patrick (2001) and the test approach of Halvorsen and Smith (1991), Chermak and Patrick (2002) do not reject the theory.

[2] Table 2.1 is a slightly extended version of Table 1 in Chermak and Patrick (2002).

Table 2.1: Overview of different tests of the theory of nonrenewable resources

Article	Test type	Time	Level	Product	Market	Exploration	Result
Barnett and Morse (2013)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Smith (1979)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Slade (1982)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Farrow (1985)	Explicit price behavior	Monthly	Single mine	Metals	Price taking	Not considered	Reject
Miller and Upton (1985)	Explicit price behavior	Monthly	Firm	Oil/gas	Price taking	Not considered	Mixed
Stollery (1983)	Explicit price behavior	Annual	Firm	Nickel	Price leader	Not considered	Do not reject
Young (1992)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Reject
Slade and Thille (1997)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Do not reject
Halvorsen and Smith (1991)	Impl. price behavior model, expl. price behavior test	Annual	Cross-industry	Metals	Price taking	Not considered	Reject
Chermak and Patrick (2001)	Implicit price behavior	Monthly	Individual well	Natural gas	Price taking	Not considered	Do not reject
Caputo (2011)	Implicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	-

Assumptions of perfect competition or monopoly market structure for nonrenewable resource markets have been the norm ever since Hotelling (1931). The idea that this may not be an appropriate assumption for the mining industry was first empirically shown by Ellis and Halvorsen (2002). They extend the general Hotelling framework with respect to a one-shot Nash-Cournot oligopoly and find that prices substantially exceed marginal costs in an application to the international nickel industry. However, these mark-ups can be attributed to a large extend to market power rather than the resource scarcity rent.

The impact of exploration activities and an extension of the resource base on the Hotelling framework was first investigated by Pindyck (1978). By allowing the firm to simultaneously decide on exploration activities (with certain outcomes) and resource extraction, they find that exploration activities and the resource price and production path are related: With an increase in reserves comes an increase in production. However, as the discovery of further reserves and, hence, the exploration activity declines, production also decreases. Subsequent research on exploration in the context of nonrenewable resources was surveyed by Cairns (1990) as well as Krautkraemer (1998). A noteworthy empirical application was made by Pesaran (1990). By investigating exploration and production decisions for oil at the United Kingdom continental shelf, they find a reasonable degree of support for the theoretical consideration of exploration in the Hotelling framework.

Our paper contributes to the existing stream of literature in several ways: First, we extend the literature on empirical tests of Hotelling's theory by means of incorporating two important features of nonrenewable resource industries, namely, combining the theoretical extensions found in Ellis and Halvorsen (2002), with regard to market power, and Pindyck (1978), with regard to exploration activity. Second, we conduct an implicit price behavior test in the spirit of Halvorsen and Smith (1991) using a newly constructed data set for the uranium mining industry. In order to address data limitations, we apply a multiple imputations approach. Third, despite obtaining negative test results, our analysis allows us to provide suggestions for why firms may not optimize inter-temporally. More specifically, we find that among others market power mark-ups may cast a shadow on the scarcity rent and therefore incentivize short-term rather than long-term planning.

Table 2.2: Notation

Abbreviation	Explanation
State variables	
χ	Cumulative resource additions
S	Amount of proven resources
Control variables	
E	Extraction rate
Q	Rate of final output
B	Exploration expenses
Parameters	
T	State of technology
P	Market price of final output
W	Market price of reproducible inputs (labor, capital)
X	Amount of reproducible inputs (labor, capital)
r	Real interest rate
λ_1	Shadow price of reserves (i.e., resource in situ)
λ_2	Shadow price of cumulative discoveries
Functions	
f	Exploration function
R	Revenue function
U	Utility function
V	Firm-specific factor prices of competing firms
Y	Exogenous global demand shifters
CR	Restricted cost function
FTC	Full total costs
FMC	Full marginal costs
Subscripts	
K	Capital
L	Labor
CAP	Global thermal capacity of nuclear power plants
MFM	Recycled warheads ("Megatons for Megawatts")
INV	Changes in global uranium inventories
LAU, LKZ	Labor Australia, Kazakhstan
KAU, KKZ	Capital Australia, Kazakhstan
SAU, SKZ	Proven reserves Australia, Kazakhstan

2.3 Theoretical Model

We consider the optimization problem of a resource extracting and processing firm. The firm faces an inverse residual demand function which is assumed to be given by

$$P(t) = P\left(Q(t), T(t), Y(t), V(t)\right), \tag{2.1}$$

where P denotes the price of the firm's final product, Q the quantity of the firm's product, Y a set of exogenous demand shifters entering the demand system and V the firm-specific factor prices of the other firms including, e.g., location-dependent costs for labor and capital. The observable arguments of the residual demand curve are threefold: own quantity, structural demand variables and the other firm's cost variables. Modeling of inverse residual demand curve hence closely follows Baker and Bresnahan (1988).

The firm is assumed to maximize its profits U, which are defined as revenues minus full total costs FTC:

$$U(t) = P(t) \cdot Q(t) - FTC(t). \tag{2.2}$$

The necessary first order condition gives

$$FMC(t) = \frac{\partial FTC(t)}{\partial Q(t)} = P(t) + \frac{\partial P(t)}{\partial Q(t)} \cdot Q(t), \tag{2.3}$$

where FMC denotes the firm's full marginal costs, obtained by taking the derivative of the firm's full total cost with respect to its own quantity.

In order to derive the firm's full marginal costs, we have to analyze the firm's decision-making process in more detail. The firm operates a two-stage production process: In the first stage of production, a nonrenewable resource is extracted and fed into the second stage of production, where it is processed into a final output. We thus assume a vertically integrated firm, which holds true for most companies in resource industries. The production function of the firm is given by

$$Q(t) = Q(E(t), X(t), S(t), T(t)), \tag{2.4}$$

where E is the extraction rate of the nonrenewable resource, X is the amount of reproducible inputs (i.e., capital and labor), S the amount of proven resources and T the state of technology.

Dual to this cost function is the restricted cost function of reproducible inputs, CR, which is defined by

$$CR(t) = CR(Q(t), E(t), W(t), S(t), T(t)) \tag{2.5}$$

with W denoting the market price of the reproducible inputs (see, e.g., Halvorsen and Smith, 1984). The firm's decision-making process is then given by the following (generalized) Hotelling model

$$\max_{E(\tau),Q(\tau),B(\tau)} \int_t^{\overline{T}} e^{-r(\tau-t)} \left[R(Q(\tau)) - CR(Q(\tau), E(\tau), W(\tau), S(\tau), T(\tau)) - B(\tau)\right] d\tau \tag{2.6}$$

$$\text{subject to:} \quad \dot{\chi}(\tau) - E(\tau) = \dot{S}(\tau) \tag{2.7}$$

$$f(B(\tau), \chi(\tau)) = \dot{\chi}(\tau) \tag{2.8}$$

$$S(\tau), Q(\tau), B(\tau), \chi(\tau), E(\tau) \geq 0. \tag{2.9}$$

As shown in Equations (2.7) and (2.8), our model incorporates the exploration activities of the firm: Given a certain effort B and already discovered resources χ, new resources $\dot{\chi}$ are found by means of the exploration function $f(B, \chi)$. Consequently, the available stock is equal to discoveries minus extracted quantities. Pindyck (1978) introduced the concept of exploration into the Hotelling framework, arguing that producers "are not endowed with reserves but must develop them through the process of exploration" (Pindyck, 1978). Therefore, the producer's choice set is increased by the decision to invest in exploration activities. The approach in this article is to assume a set of characteristics for the exploration function f. Those include (i) increasing discoveries with increasing exploratory expenditures, (ii) diminishing marginal productivity and (iii) the discovery decline condition (see, e.g., Pesaran, 1990). Letting λ_1 and λ_2 denote the costate variables (or shadow prices) of Equations (2.7) and (2.8), we derive the Hamiltonian of the optimization problem as

$$\begin{aligned} H(t) &= R(Q(t)) - CR(Q(t), E(t), W(t), S(t), T(t)) - B(t) - \lambda_1(t) \cdot (\dot{\chi}(t) - E(t)) \\ &\quad -\lambda_2(t) \cdot f(B(t), \chi(t)). \end{aligned} \tag{2.10}$$

In the following, time arguments are omitted for improved readability. The static optimality conditions, i.e., the first-order conditions of Equation (2.10) with respect to the control variables E, B and Q, are given by

$$0 = -\frac{\partial CR}{\partial E} + \lambda_1 \tag{2.11}$$

$$0 = -1 - (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial B} \tag{2.12}$$

$$0 = \frac{\partial R}{\partial Q} - \frac{\partial CR}{\partial Q}. \tag{2.13}$$

Following the maximum principle, Equations (2.11) to (2.13) state that the Hamiltonian has to be maximized by the control variables in every point in time t (Chiang, 2000). Rearranging Equations (2.11) and (2.12), the static optimality conditions result in the following equations for the shadow prices λ_1 and λ_2:

$$\lambda_1 = \frac{\partial CR}{\partial E} \tag{2.14}$$

$$\lambda_2 = -\left(\frac{\partial f}{\partial B}\right)^{-1} - \frac{\partial CR}{\partial E}. \tag{2.15}$$

The interpretation of Equations (2.13), (2.14) and (2.15) is rather straightforward. Equation (2.13) states that the firm chooses output quantity Q such that the marginal revenue equates the marginal changes in restricted costs CR. Equation (2.14) states that extraction is optimally chosen if marginal changes in restricted costs (due to changes in extraction E) correspond to the shadow price of the resource in situ λ_1. Finally, Equation (2.15) gives the relationship between the shadow price of exploration λ_2 and changes in the exploration function f with respect to exploration expenditures B as well as the shadow price of the resource in situ, which is equivalent to the marginal changes in restricted costs with respect to extraction E. This illustrates that, even though the restricted cost does not directly depend on the exploration activities, a connection exists via the amount of proven resources S and the values λ_1 and λ_2.

The dynamic optimality conditions of the generalized Hotelling model follow from the relation of the choice for the control variables and the state variables. The dynamic optimality conditions give the optimal path for the shadow prices (see, e.g., Chiang, 2000, Wälde, 2012)

$$\dot{\lambda}_1 = \frac{\partial CR}{\partial S} + r \cdot \lambda_1 \qquad (2.16)$$

$$\dot{\lambda}_2 = (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial \chi} + r \cdot \lambda_2. \qquad (2.17)$$

Inter-temporal changes in the shadow price of the resource in situ λ_1 equate changes in restricted costs CR with respect to the amount of proven resources S and the changes in interest rates r. Similar, inter-temporal changes in λ_2 result from variations in the interest rates but also from changes in the exploration function f with respect to cumulative resource additions χ[3], weighted by both shadow prices.

2.4 Econometric Model

The restricted cost function covers different variable types: E is an intermediate good, X_L and X_K are production inputs of capital and labor, respectively, Q is the output of the final good, and S is an environment variable. We approximate the true restricted cost function using an transcendental logarithmic (translog) functional form (see, e.g., Ellis and Halvorsen, 2002, Ray, 1982). The small time-span covered by our data (compared to innovation cycles in mining industries) allows us to exclude the state of the technology T from the cost function. Therefore, the interaction terms of the translog-representation of the restricted cost function are limited to the intermediate as well as the production input and output variables. We median-adjust our independent variables, allowing for first-order coefficient estimates to be interpreted as cost elasticities at the sample median (Last and Wetzel, 2010).

[3]By the discovery decline condition: $\frac{\partial f}{\partial \chi} < 0$.

The restricted cost function is given by

$$\begin{aligned}
\ln CR &= \alpha_0 + \alpha_Q \ln Q + \sum_j \alpha_j \ln W_j + \alpha_E \ln E + \alpha_S \ln S \\
&+ \frac{1}{2}\sum_j \sum_k \gamma_{jk} \ln W_j \ln W_k + \frac{1}{2}\gamma_{QQ}(\ln Q)^2 + \frac{1}{2}\gamma_{EE}(\ln E)^2 \\
&+ \sum_j \gamma_{jQ} \ln W_j \ln Q + \sum_j \gamma_{jE} \ln W_j \ln E + \gamma_{QE} \ln Q \ln E \qquad (2.18)
\end{aligned}$$

with $j \in \{K, L\}$ and L and K being subscripts for labor and capital. Symmetry and homogeneity of degree one in inputs are given by the following restrictions:

$$\begin{aligned}
\gamma_{KL} &= \gamma_{LK} \\
\sum_j \alpha_j &= 1 \\
\sum_j \gamma_{jQ} &= \sum_j \gamma_{jE} = \sum_j \gamma_{jk} = \sum_j \gamma_{kj} = 0. \qquad (2.19)
\end{aligned}$$

We impose homogeneity in prices by dividing by one price and thus account for just one price in the estimation. Symmetry conditions are imposed directly into the model.

In order to increase estimation efficiency, we incorporate cost share equations into our system of equations. The cost share equations for production inputs follow directly from the logarithmic differentiation of the implicit cost function with respect to input prices (Ray, 1982):

$$M_K = \alpha_K + \sum_j \gamma_{Kj} \ln W_j + \gamma_{KQ} \ln Q + \gamma_{KE} \ln E \qquad (2.20)$$

$$M_L = \alpha_L + \sum_j \gamma_{Lj} \ln W_j + \gamma_{LQ} \ln Q + \gamma_{LE} \ln E \qquad (2.21)$$

with $M_K = W_K X_K / CR$ and $M_L = W_L X_L / CR$ equal to the shares of reproducible inputs in restricted cost.

Following Equation (2.3), the supply relation requires an expression for full marginal costs (FMC), which are given by the partial derivative of full total costs (FTC) with respect to output quantity Q.

In our model, FTC are represented by the sum of restricted costs, exploration expenditures, the shadow price of the resource in situ multiplied by the changes in resource stock and the shadow price of exploration multiplied by the discoveries from exploration:

$$FTC = CR + B + \lambda_1 (f - E) + \lambda_2 f. \qquad (2.22)$$

From this, we derive the FMC as

$$FMC = \frac{\partial FTC}{\partial Q} = \frac{\partial CR}{\partial Q} + \frac{\partial CR}{\partial E}\frac{\partial E}{\partial Q} - \lambda_1 \frac{\partial E}{\partial Q} = \frac{\partial CR}{\partial Q} \tag{2.23}$$

given the firm sets E at its optimal level. Therefore, the full marginal costs contain no direct expression of the unknown shadow prices λ_1 and λ_2 and therefore can be estimated without further transformations (see also Ellis and Halvorsen, 2002).[4] An expression for the right-hand side is obtained inserting the specification for the restricted cost function, i.e., Equation (2.18):

$$\begin{aligned} FMC = \frac{\partial CR}{\partial Q} &= \frac{\partial \ln CR}{\partial \ln Q}\frac{CR}{Q} \\ &= (\alpha_Q + \gamma_{QQ} \ln Q + \sum_j \gamma_{jQ} \ln W_j + \gamma_{QE} \ln E)\frac{CR}{Q}. \end{aligned} \tag{2.24}$$

The relationship between the firm's own price and quantity and the other firms' supply responses is given by the inverse residual demand curve, which we specify following the methodology introduced in Baker and Bresnahan (1988). In other words, the inverse residual demand curve of the firm of interest covers the firm's price P and quantity Q as well as the other firms' factor prices V and global demand shifters Y. As shown in Baker and Bresnahan (1988), estimation results are not sensitive to the particular specification (i.e., log-log or linear-linear) of the inverse residual demand curve. For our application, it is convenient to apply a linear-log specification as it simplifies further calculations. Thus, the residual demand curve is specified as follows (Baker and Bresnahan, 1988):

$$P = \beta \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l. \tag{2.25}$$

In order to allow for time-varying mark-ups, we apply a semi-parametric approach following Ellis and Halvorsen (2002) and Diewert (1978) and represent β as a polynomial function in time. In the subsequent estimation procedure, we estimate different functional specifications for the polynomial representation of β. Overall, we find robust estimation results among different specifications for $\beta(t)$. Results suggest that specifying the mark-up term as a biquadratic polynomial yields satisfactory results. Further insights on this procedure are displayed in Appendix A.1. It follows the inverse residual demand curve as

$$P = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4) \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l. \tag{2.26}$$

[4]Note however, that the price of the resource in situ is included in the full marginal costs.

Having specified the FMC (Equation (2.24)) as well as the inverse residual demand curve (Equation (2.26)), we can transform and use these estimation equations to obtain the estimation equation for the supply relation, i.e., Equation (2.3). First, we take the first derivative of price with respect to firm quantity

$$\frac{\partial P}{\partial Q} = \frac{\partial P}{\partial \ln Q}\frac{\partial \ln Q}{\partial Q} = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4)\frac{1}{Q}. \tag{2.27}$$

The supply relation for estimation follows as

$$P = (\alpha_Q + \gamma_{QQ}\ln Q + \sum_j \gamma_{jQ}\ln W_j + \gamma_{QE}\ln E)\frac{CR}{Q} - (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4). \tag{2.28}$$

We apply the implicit price behavior test by Halvorsen and Smith (1991). In doing so, we utilize the fact that estimation of the marginal cost function, cost share equation, inverse residual demand curve and supply relation (i.e., Equations (2.18), (2.21), (2.26) and (2.28), respectively) is consistent. The resulting estimates of this model represent the static optimization problem of the firm. However it should be noted that as static optimality in each point in time is a prerequisite for dynamic optimality, this result can also represent the dynamically optimal solution. Under the null hypothesis that the firm optimally extracted its resource, within the framework of the Hotelling model, the addition of the first dynamic optimality condition given by Equation (2.16) in the system of equations should result in consistent but more efficient estimates. Under the alternative hypothesis, the extended model with the dynamic optimality condition is inconsistent. We test the null hypothesis applying a Hausman specification test.

In order to estimate the model including the dynamic optimality conditions, we first need to derive the discrete time form of the dynamic optimality condition (2.16), which is given by

$$\lambda_1(t) = \frac{\partial CR}{\partial S}(t) + (1+r)\lambda_1(t-1). \tag{2.29}$$

With

$$\lambda_1 = \frac{\partial CR}{\partial E} = \frac{\partial \ln CR}{\partial \ln E}\frac{CR}{E} = \underbrace{(\alpha_E + \gamma_{EE}\ln E + \sum_j \gamma_{jE}\ln W_j + \gamma_{QE}\ln Q)}_{a^{\lambda_1}}\underbrace{\frac{CR}{E}}_{b^{\lambda_1}} = a^{\lambda_1}b^{\lambda_1} \tag{2.30}$$

and

$$\frac{\partial CR}{\partial S} = \frac{\partial \ln CR}{\partial \ln S}\frac{CR}{S} = \underbrace{\alpha_S}_{c^{\lambda_1}}\underbrace{\frac{CR}{S}}_{d^{\lambda_1}} = c^{\lambda_1}d^{\lambda_1}, \tag{2.31}$$

we obtain

$$a^{\lambda_1}(t)b^{\lambda_1}(t) = c^{\lambda_1}(t)d^{\lambda_1}(t) + (1+r)a^{\lambda_1}(t-1)b^{\lambda_1}(t-1). \tag{2.32}$$

Summarizing, we estimate two models and apply a Hausman specification test. The two lists below summarize the equations used in each model.

Model 1 (without dynamic optimality condition):

1. The restricted cost function, Equation (2.18);
2. The cost share equation, Equation (2.21);
3. The inverse residual demand curve, Equation (2.26);
4. The supply relation, Equation (2.28).

Model 2 (with dynamic optimality condition):

1. The restricted cost function, Equation (2.18);
2. The cost share equation, Equation (2.21);
3. The inverse residual demand curve, Equation (2.26);
4. The supply relation, Equation (2.28);
5. The dynamic optimality condition, Equation (2.32).

Within our model, the market price of final output P, the quantity of final output Q, as well as the extracted resource quantities E, are endogenous and need to be treated in order to prevent biased estimates. Having to deal with endogeneity and simultaneous equations, we utilize an iterative Three-Stage-Least-Squares approach (3SLS). Despite being linear in parameters, our system of equations will be nonlinear in endogenous variables due to transformations of the endogenous variables (e.g., interactions with other variables and squaring). Even though nonlinear transformations of endogenous variables are not necessarily a problem[5], we follow Wooldridge (2002) (Chapter 9.5) and use a set of squared and higher-order transformations of exogenous variables. In addition to exogenous variables already used in our system of equations, we introduce the following instrumental variables: $\ln Q^3$, $\ln Q^4$, $\ln S^3$, $\ln S^4$, $\ln P^3$, $\ln P^4$, T and T^2.

[5]With endogeneity corresponding to correlation of one variable with the error term, nonlinear transformations may eliminate the correlation.

2.5 Data

We construct a data set for the Canadian uranium mining firm Cameco Corporation[6]. We use quarterly firm-level data for the years 2002-2012. In our estimation, we therefore work under the implicit assumption that all relevant information is consistent with this level of aggregation.

Nowadays, uranium is a mineral that is used almost entirely to fuel nuclear power plants. The market for uranium mining shows considerable concentration on the supply side, with KazAtomProm, Cameco and Areva covering almost 50% of global uranium production (as of 2013) (World Nuclear Association, 2014). These firms are vertically integrated, i.e., they extract the ore, and later mill and process it via leaching to obtain a uranium concentrate powder (yellowcake or U_3O_8) that is subsequently processed in enrichment and fuel fabrication facilities, which are usually operated by other companies. Yet, the subsequent processing steps do not alter the buyer and seller interaction, as consumers (i.e., operators of nuclear power plants) directly purchase the yellowcake from mining firms and afterwards contract subsequent fuel processing (e.g., Neff, 1984). In the past, contracting was entirely based on long term agreements. However, nowadays the spot market and spot price indices gained relevance also in terms of spot market-related contractual agreements (TradeTech, 2011).

Even though uranium itself is abundant in the earth's crust, most of the deposits are of such low concentration that production is not profitable. Deposits with relevant uranium concentration are found predominantly in Australia, Kazakhstan, Canada and Russia and hence, making these regions targets for exploratory activity by mining firms. With exploration expenditures of approx. 100 million U.S. dollars in 2012 (Cameco, 2012a) it becomes clear that exploration is an important feature of the considered firm and industry.

This short industry description illustrates that the uranium mining industry is suitable for the proposed test of Hotelling's theory for various reasons. First, firms are vertically-integrated, i.e., they are producing and processing the nonrenewable resource. Second, there is a considerable amount of market concentration. Third, exploration activity is a relevant decision variable of uranium mining firms. Fourth, because of the time-span necessary for nuclear power plants to pass authorization and construction, future demand is comparably certain compared with other mining industries. Hence, short-term price path deviations (Krautkraemer, 1998) are not to be expected. Fifth, consumption of uranium has no externalities on the climate such as other nonrenewable resources.

[6]The decision to choose Cameco was made for no particular reason other than it showed a better data availability compared to competing firms.

Therefore, environmental externalities are not expected to alter the optimal path of resource depletion. And sixth, the chemical alteration of uranium in the process of consumption in nuclear power plants makes recycling of uranium almost impossible under normal circumstances. This is contrary to most other resources used in previous tests, e.g., nickel and copper. As reintroduction of recycled resources into the system, alters the extraction path, uranium is in this regard a more suitable resource to consider.

The main data sources are introduced in the following, while a detailed description of data sources and calculation steps is given in Appendix A.3. Extraction rate E, rate of final output Q, exploration expenses B, market price of final output P, amount of proven reserves S and the amount of reproducible inputs for labor X_L and capital X_K (using the perpetual inventory method) are taken from Cameco (2012a) and Cameco (2012b). Prices for reproducible input labor W_L are based on Canadian average wages in the mining industry (Statistics Canada, 2013a), and prices for capital W_K are calculated from producer price indices, depreciation rates and real rate of interest $\tilde{r}$ (Bank of Canada, 2014b, Statistics Canada, 2013b).

The other firms' factor prices V used for the estimation of the inverse residual demand curve contain labor and capital costs as well as proven reserves. With the main competitors of Cameco active in Kazakhstan and Australia, we approximate the other firms' factor prices using values for these countries (e.g., ABS, 2014b, Agency of Kazakhstan of Statistics, 2014c, Australia, 2013). The global demand shifters Y cover the global thermal capacity of nuclear power plants (International Atomic Energy Agency, 2013), changes in global uranium inventories (Nuclear Energy Agency, 2011) and market quantities from military warhead recycling through, e.g., the "Megatons to Megawatts Program" (Centrus, 2014).

Specification of the exploration function f is done by testing different functional forms using available firm-level data as well as extended data sets on Canadian exploration expenditures and discoveries (Nuclear Energy Agency, 2006). As no functional form proved consistent with (*i*) increasing discoveries with increasing exploratory expenditures, (*ii*) diminishing marginal productivity and (*iii*) the discovery decline condition, we have to assume that the multiplicative error term in the discovery function is large. Given the relatively low number of observations available, it makes it impossible to accurately estimate the exploration function.

Therefore, we use a functional form that deviates from the theoretic relationship specified in Equation (2.8). In the following, we use a simplified variant, given by $\dot{\chi} = f(B)$:

$$\dot{\chi}(t) = B(t)^{\underset{(11.1)}{0.4829}} \omega(t). \tag{2.33}$$

The error term associated with exploration activities is given by ω. The value in brackets below the exponent of the exploratory expenditures B represents the resulting t-value for this model.

This specification satisfies the conditions (i) and (ii) but can not account for the discovery-decline phenomenon (iii). The insignificance of the discovery-decline condition could correspond to numerous global discoveries made in recent years (similar results are obtained by Pesaran, 1990).

While quarterly data for exploration expenditures B are published by the firm (see also Appendix A.3), the amount of proven reserves S and hence resource additions $\dot{\chi}$ are only available on an annual basis. Therefore, we follow Little and Rubin (2002) and use the exploration function f to impute the resource additions $\dot{\chi}$. By using a multiple imputation approach, we create fifty different time series for the amount of resource additions $\dot{\chi}$ and hence, proven reserves S. Thus, we have 50 different data subsamples that are identical except for S and $\dot{\chi}$. We estimate each subsample individually. Using quarterly data from 2002 to 2012 yields 44 unique observations per variable and subsample.[7]

2.6 Empirical Results

Prior to comparing the estimates for Model 1 and Model 2, we first need to define the interest rate r in the dynamic optimality condition Equation (2.32) of Model 2. We test the Hotelling model using different interest rates. Following Halvorsen and Smith (1991), we test constant discount rates ($r = 0.01$ to 0.25) as well as variable interest rates that are proportional to actual real (2012) Canadian interest rates $\tilde{r}$ ($r = \tilde{r} \cdot 0.25$ to $\tilde{r} \cdot 4$). This results in a total of 41 different interest rate settings to be tested. Having 50 data subsamples and 41 different interest rates gives a total of 50 estimation results for Model 1 (i.e., one result per individually estimated subsample) and 2050 estimation results for Model 2 (i.e., one result for every combination of the 50 subsamples with the 41 different interest rates). In order to make the estimation results as tractable as possible as well as to illustrate the distribution of results appropriately, we present the mean values of estimates together with their standard deviation.

Our test results indicate a rejection of the null hypothesis for both the constant discount rate (see Table 2.3) and the variable interest rate calculations (see Table 2.4) at least at the 5%-level (except for two cases, which are significant at the 10%-level). Within our

[7]Obtaining a larger sample size is often impossible in the mining industry. Hence, 40 to 50 observations can be considered standard in this respect (e.g., Ellis and Halvorsen, 2002).

modeling approach, these results suggest that the firm's behavior does not satisfy the dynamic optimality condition.[8]

Table 2.3: Hausman test results for constant interest rates

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	900.037	1038.959	0.047**	0.191
0.02	1181.12	1966.562	0.013**	0.056
0.03	1051.912	1385.697	0.028**	0.112
0.04	979.57	1254.118	0.045**	0.191
0.05	1035.038	1269.951	0.052*	0.218
0.06	1064.868	1526.222	0.026**	0.154
0.07	1262.86	1876.377	0.033**	0.143
0.08	1025.725	1240.366	0.029**	0.157
0.09	1151.013	1608.189	0.046**	0.18
0.1	1112.523	1648.475	0.024**	0.154
0.11	1041.461	1240.148	0.02**	0.129
0.12	1045.752	1220.42	0.025**	0.141
0.13	1037.033	1255.913	0.043**	0.196
0.14	1097.268	1434.342	0***	0.001
0.15	2846.733	11971.337	0.018**	0.111
0.16	1193.924	1847.219	0.046**	0.21
0.17	1178.983	1453.245	0.002***	0.011
0.18	1110.566	1521.609	0.008***	0.054
0.19	1005.5	1233.742	0.024**	0.151
0.2	925.503	1168.636	0***	0.003
0.21	1049.172	1282.834	0.019**	0.12
0.22	945.77	1134.375	0.024**	0.152
0.23	939.674	1130.028	0.004***	0.024
0.24	954.936	1159.637	0.023**	0.151
0.25	1530.604	3029.573	0***	0

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

[8] In 326 models of the 2050 combinations of subsamples and interest rates, we find near-singular matrices. This collinearity is not originating from a particular set of subsamples or interest rates, but rather different combinations of them. Therefore, this statistical issue should be solely based on the inappropriateness of certain interest rates for the rest of the data.

Table 2.4: Hausman test results for proportional variations of the actual Canadian interest rate r

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	1682.839	5031.267	0.029^{**}	0.151
$r \cdot 0.5$	1141.45	186.521	0.015^{**}	0.076
$r \cdot 0.75$	973.025	194.366	0.08^{*}	0.251
$r \cdot 1$	1139.035	172.047	0.05^{*}	0.213
$r \cdot 1.25$	1073.7	203.451	0.026^{**}	0.154
$r \cdot 1.5$	1179.135	179.52	0.034^{**}	0.152
$r \cdot 1.75$	1044.678	217.54	0.053^{*}	0.22
$r \cdot 2$	1509.901	209.176	0.025^{**}	0.148
$r \cdot 2.25$	1049.269	261.291	0.022^{**}	0.143
$r \cdot 2.5$	1024.811	279.253	0.025^{**}	0.147
$r \cdot 2.75$	1056.235	163.517	0.041^{**}	0.166
$r \cdot 3$	1210.659	159.604	0^{***}	0
$r \cdot 3.25$	1307.49	180.983	0.046^{**}	0.207
$r \cdot 3.5$	2358.77	211.189	0.004^{***}	0.023
$r \cdot 3.75$	1110.498	233.241	0.018^{**}	0.116
$r \cdot 4$	1147.636	231.08	0.004^{***}	0.028

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Even though the null hypothesis is rejected, estimation results of Model 1 provide information on cost factors, market power and the shadow price of the resource in situ. Table 2.5 gives the related mean values and standard deviations for coefficients, standard errors and p-values.[9],[10]

[9] Tables A.5, A.6, A.7 in Appendix A.3 provide quantiles and further descriptions of the distribution of coefficient estimates, p-values and standard errors of the Model 1 estimation results.

[10] Note that $\gamma_{KK} = -\gamma_{LK} = \gamma_{LL} = -\gamma_{LK}$.

Table 2.5: Estimation results for Model 1

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.715	0.034	3.14E-32***	1.51E-31	0.105	7.41E-3
α_Q	1.57E-8	1.92E-9	3.25E-5***	2.28E-5	2.82E-9	2.02E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.26E-5	1.36E-45***	4.13E-46	1.11E-4	1.88E-6
α_E	2.116	0.092	9.23E-9***	1.49E-8	0.211	0.015
α_S	-0.204	0.134	0.174	0.219	0.116	0.039
γ_{KK}	-4.72E-4	1.90E-4	0.237	0.161	3.49E-4	4.20E-5
γ_{QQ}	1.34E-8	2.46E-9	0.104+	0.050	7.58E-9	5.80E-10
γ_{EE}	1.665	0.313	0.031**	0.059	0.606	0.090
$\gamma_{KQ} = -\gamma_{LQ}$	-9.39E-9	1.56E-9	0.021**	0.023	3.47E-9	3.12E-10
$\gamma_{KE} = -\gamma_{LE}$	2.35E-3	6.44E-5	2.89E-8***	2.27E-8	2.59E-4	6.83E-6
γ_{QE}	-1.93E-8	2.14E-9	5.68E-4***	4.14E-4	4.53E-9	4.36E-10
β_0	-18.297	1.909	7.66E-4***	2.18E-3	3.910	0.270
β_1	0.038	0.090	0.741	0.188	0.209	0.020
β_2	0.112	0.017	1.11E-3***	8.78E-4	0.028	2.61E-3
β_3	-8.98E-4	2.32E-4	0.318	0.133	8.45E-4	6.83E-5
β_4	-1.84E-4	3.81E-5	0.011**	8.55E-3	6.13E-5	5.87E-6
τ_{MFM}	14.216	8.742	0.617	0.176	26.319	1.589
τ_{CAP}	93.717	17.295	0.324	0.096	91.125	4.263
ϱ_{LAU}	14.580	1.400	0.028**	0.014	6.012	0.123
ϱ_{LKZ}	10.609	1.984	0.076*	0.074	5.183	0.282
ϱ_{KAU}	25.376	3.004	0.049**	0.031	11.694	0.778
ϱ_{KKZ}	8.555	0.811	0.041**	0.025	3.809	0.205
τ_{INV}	10.713	0.101	3.66E-16***	8.69E-17	0.419	4.96E-3
ϱ_{SAU}	19.788	2.295	0.016**	8.31E-3	7.268	0.276
ϱ_{SKZ}	-4.434	2.130	0.513	0.210	6.446	0.373
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.55 std. dev. 0.05, Eq. (2.21): mean 0.68 std. dev. 0.02, Eq. (2.26): mean 0.02 std. dev. 0.22, Eq. (2.28): mean 0.55 std. Dev. 0.05					

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

Given the logarithmic form in Equation (2.19) as well as the convergence point set at the sample median, first-order coefficients for this equation represent the logarithmic first-order partial derivatives of the cost function and, thus, the cost elasticities at the sample median. Alternatively, the level-log specification of Equation (2.26) gives the absolute change in prices P under a percentage change in the independent variables (i.e., own quantity Q, the other firms factor prices V and global demand shifters Y).

A majority of coefficients are statistically significant at the 1%- and 5%-level. Furthermore, the first-order coefficients for the cost function (2.19) follow intuition: costs increase with higher costs for labor, capital, increased extraction and higher final output. Larger reserves tend to result in lower extraction costs. This estimate is not statistically significant at the 10%-level for all, but some subsamples. The mean p-value is at 0.238 with a standard deviation of 0.256. This illustrates that a considerable amount of subsamples give statically significant results also for the amount of reserves. With respect to the inverse residual demand function in Equation (2.26), the coefficients for own quantity is of the expected sign whereas the other coefficients have no clear interpretation as they reflect direct and indirect effects due to adjustments made by competing firms (Baker and Bresnahan, 1988). The estimated coefficients are of plausible magnitude.[11]

Apart from our main finding, that the firm seems to fail to optimize inter-temporally, the estimation results for the cost function allow us to also highlight firm/industry cost characteristics. First, processing of the good into the final output is much less cost intensive as is the extraction of the resource: Increasing extraction E by 1% corresponds to an average approximate increase in costs by 2.414%, whereas increasing output Q by 1% hardly changes costs. Second, increasing the reserves, i.e., the resource base, by 1% through exploration results in an average approximate reduction in production costs of 0.188%.

The estimation results allow us to to directly calculate the market power mark-up in Equation (2.23) from the difference in the market price of final output P and $\partial CR/\partial Q$, which equals the FMC if the firm optimally chooses its control variables. Note that the FMC also include the price of the resource in situ.

Figure 2.1 illustrates the Lerner index calculated from our model.[12] The mean value of the Lerner index is given by the solid line, while the dark gray ribbon illustrates the standard deviation from the mean values. The light gray ribbon captures all subsample results. The graph clearly shows a substantial mark-up over marginal costs of approximately 0.5 for the first half of the last decade and a clearly decreasing trend towards zero in the first half of 2012. Given that the mark-up corresponds to such a large share of the final output price for most of the observations, it becomes apparent that firms may optimize their output with respect to this mark-up rather than the optimal depletion of the resource.

[11]Due to the logarithmic form of the restricted cost function, all α- and γ-coefficients represent percentage changes in the dependent variable with respect to changes in the corresponding independent variables. Therefore, plausible magnitudes are single-digit. Under the level-log specification of the inverse residual demand curve, all β-, τ- and ϱ-coefficients give level changes in the dependent variable, i.e., P, with respect to percentage changes in the independent variables. As the price levels vary between 31.75 and 57.38 (see Table A.14), plausible coefficient magnitudes are in the lower half of the two-digit spectrum.

[12]The Lerner index is given by $(P - \partial CR/\partial Q)/P$.

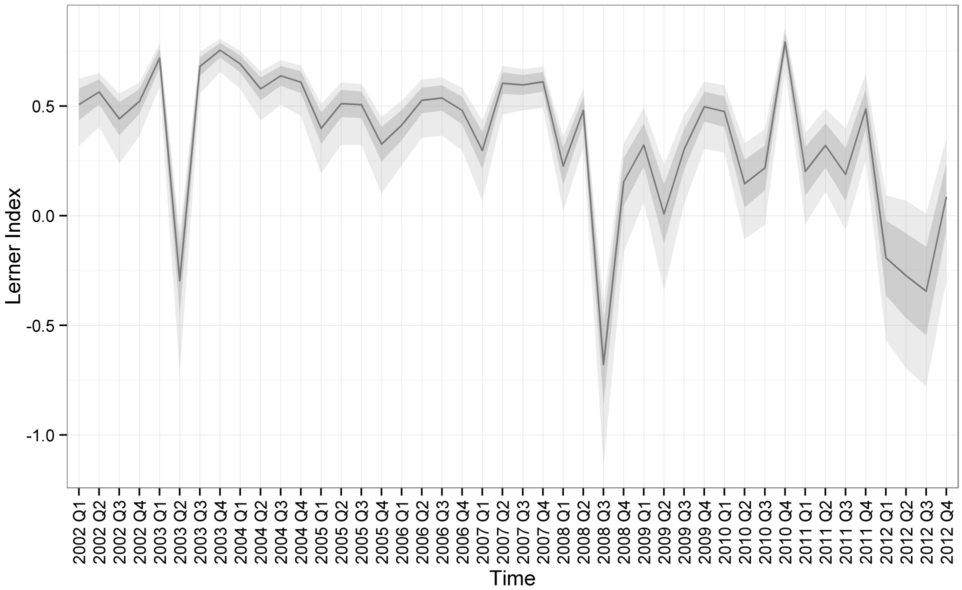


Figure 2.1: Lerner index

However, Figure 2.1 shows that the mean value of the Lerner index drops below zero in five observations. This represents prices below FMC. The latter four points suggests that shocks from the global financial crisis in 2008 and the shut down of several nuclear power plants in the aftermath of the Fukushima nuclear disaster might be the source of these results. We test these suggestions (see Appendix A.2) and find that there seems to be no shock effect impacting global price setting at these observations. As for 2003 Q2, no immediate explanation for the negative value can be given.

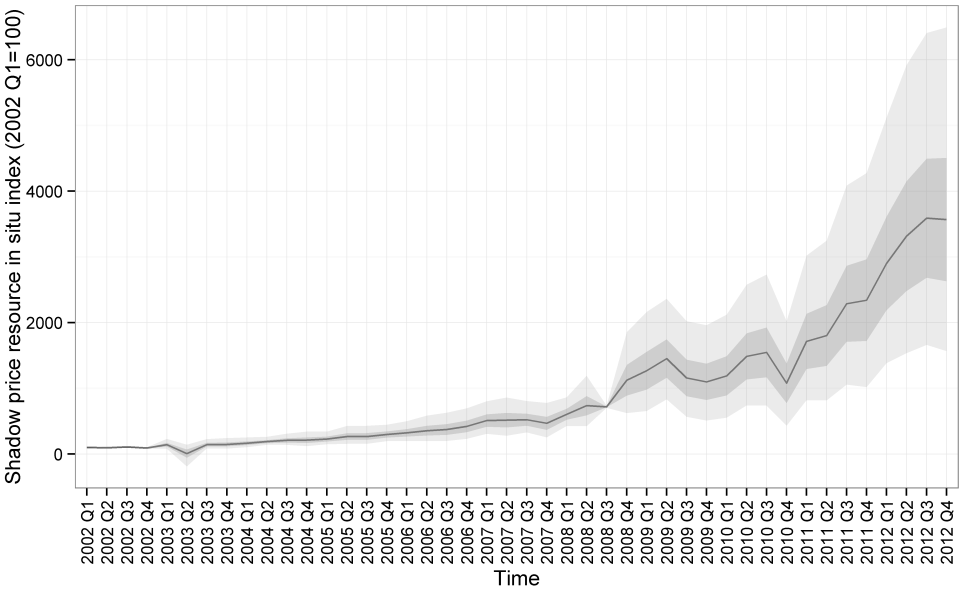


Figure 2.2: Indexed shadow price of the resource in situ (2002 Q1=100)

Further conclusions can be drawn from the development of the shadow price (i.e., the scarcity rent) of the resource in situ. For this, we derive an index of scarcity, as done in Halvorsen and Smith (1984), by computing an indexed version of the shadow price λ_1 given in Equation (2.30). The value for the first quarter of 2002 is set at 100. Figure 2.2 shows a drastic increase in shadow price of the resource in situ and, thus, an increasing scarcity of the resource. The solid line represents the mean value, the dark gray ribbon gives the standard deviation and the light gray ribbon illustrates the minimum and maximum values, similar to Figure 2.1. The nonexistence of ribbons at 2008 Q3 suggests that there is a data issue of some sort as the source of the negative spike in the Lerner index. The steep increase in the shadow price at the latter observations might be the source of the negative Lerner index for 2012 Q2 and Q3. While the relative market power mark-up is large at the beginning of the observations, the firm might have based extraction decisions mainly on mark-ups originating from market power. However, for the latter observations, the shadow price of the resource in situ increases steeply and the firm fails to incorporate this development in their price setting. As the shadow price of the resource in situ is a part of the FMC, this might explain the negative Lerner index.

2.7 Discussion and Conclusions

In this paper, we conduct an implicit price behavior test based on the methodology introduced by Halvorsen and Smith (1991). We extend the literature on tests of Hotelling's theory by incorporating for the first time the concepts of market power, as introduced by Ellis and Halvorsen (2002), and exploration, as in (Pindyck, 1978) into a single model. Applying the test to a newly constructed data set for the uranium mining industry, we reject the null hypothesis of the firm optimizing inter-temporally. This complements prior research, which mostly failed to find evidence for the empirical validity of Hotelling's model.

Parameter estimates show that there exists a substantial mark-up over marginal costs that does not account for the shadow price of the resource in situ for the earlier observations and lower and even negative mark-ups over marginal costs for later observations. For the earlier observations, only a very small share of market prices can possibly represent resource user costs. This changes as the shadow price of the resource in situ increases steeply over time. The negative mark-up illustrates that the firm fails to assess the shadow price appropriately. Our results suggest that the hypothesis of Halvorsen (2008) partly holds, i.e., that the shadow price of the resource in situ may be too small to be considered in a firm's decision-making process and that the *mistake* firms are making by not optimizing inter-temporally optimal may be small. Nonetheless, we find that even as the shadow price increases steeply, firms fail to incorporate this development appropriately in their price setting.

Furthermore, and as already stated by Halvorsen and Smith (1991), inadequacy of the theoretical model could be another likely reason for the theory to be rejected. Possible reasons for this inadequacy can be found in the assumptions made in the model. As we assume a uniform price for the good, we omit issues of transaction costs and imperfect information (also regarding foresight).

Similar to the tests previously performed in other analyzes, our results put the predictive power of the theory for nonrenewable resources into question. However, regardless of the (comparably) predictable uranium demand due to long nuclear reactor construction times, uncertainty prevails in the market, e.g., as a result of unknown international inventories. Therefore, relaxing the assumption regarding perfect foresight could be a promising next step in testing the theory of nonrenewable resources.

Chapter 3

Models of endogenous production capacity investment in spatial oligopolistic markets

This paper introduces two different models of production capacity investment and supply in spatial oligopolistic markets. In the models explored in the paper, players make decisions about investment in production capacity and supplies to each market. Supplies are constrained by the players' production capacity and are therefore dependent on both their existing capacities and the investment decision. Markets and players are spatially dispersed which leads to asymmetry in the cost structures. Two different time structures regarding players' decisions are analyzed: In the 'open-loop' model, which represents a market based on long-term contracts, investment and supply decisions are taken simultaneously (e.g. the product is sold at the moment the investment decision is taken). In the 'closed-loop' model, which represents a market based on spot markets, players decide on supply, given observed prior investment decisions. For a two node-two player Cournot electricity market setting, the paper presents an existence and uniqueness result for the open-loop model and discusses criteria for investment and supply results for the two models to coincide or differ. The paper concludes that closed-loop investments and supplies are larger or equal than those resulting in the corresponding open-loop model, leading to higher consumer surplus in the closed-loop model.

3.1 Introduction

Spatial oligopolies are characterized by a small number of producers supplying regionally separated markets. Next to the production costs, transportation costs and transportation constraints are important determinants in these markets. Resource markets, like those for oil, gas and coal as well as electricity markets are the prototype examples of spatial oligopolies as these markets typically feature a small number of large players and are generally not fully competitive.

Because of its theoretical and empirical importance, spatial oligopolies have been studied extensively in economic research. This includes empirical work analyzing market structure, trade flows and prices in resource markets, e.g., for steam coal markets (Haftendorn and Holz, 2010, Kolstad and Abbey, 1984, Trüby and Paulus, 2012), metallurgical coal markets (Graham et al., 1999, Trüby, 2013), natural gas markets (Gabriel et al., 2005, Growitsch et al., 2013, Holz et al., 2008, Zhuang and Gabriel, 2008), wheat markets (Kolstad and Burris, 1986), oil markets (Huppmann and Holz, 2012) or for iron ore markets (Hecking and Panke, 2014) as well as for electricity markets (Jing-Yuan and Smeers, 1999, Lise et al., 2006).

Previous work on spatial oligopolies has mostly ignored investment decisions, despite the fact, as highlighted for instance in Huppmann (2013), that the capacity constraints used in the analysis strongly impact the results. Huppmann (2013) therefore extends the model to account for endogenous capacity expansion assuming simultaneous decisions on supply and investment volumes by the players. This can be interpreted as pointed out in Murphy and Smeers (2005) as a market organized along long-term contracts, i.e., at the moment the investment decision is taken the product is sold. This clearly is an accurate description for some markets and may also serve as a good approximation to other markets.

However, in recent years, there is a gradual shift away from long-term contracted trading towards spot-market based trading in several important energy markets. Examples can be found for resource markets, like the coking coal market or the market for liquified natural gas. Electricity markets are also increasingly governed by a mix of long-term and spot-market based trade.

The difference in market structure not only influences trade flows, prices and supply decisions but also investment decisions. A priori it is not clear whether more spot-market based trade will result in higher investment or not. First, long-term trade reduces risk for investors and might therefore create a more stable environment for investments which should lead to more investments than under spot-market based trade. Second, it might also be argued that the inability of a producer to commit over a longer term to a production profile under spot-market based trade corresponds to a higher degree of competition and therefore leads to higher investment than under long-term based trade. With players anticipating this strategic effect, however, it is not clear how this will play out and an easy ranking of the different market outcomes is not obvious.

In light of this debate, this paper analyzes the influence of different market structures on investment decisions and market outcomes in deterministic spatial oligopolies. Two market structures are considered: In the first model, the so-called open-loop Cournot model, players decide simultaneously on their supplies and investments. This can be interpreted as a market organized along long-term contracts. In the second model, players play a two-stage game. In the first stage, players decide on their investment level. In the second stage, having observed the investment decisions of all players, a spot market game is played, i.e., players decide on their production levels. This type of model is called a closed-loop Cournot model and can be interpreted as a market organized along spot-market trade.

The effect on investment decisions and market outcome from moving from long-term contract based trading towards spot-market based trading was first systematically analyzed in Murphy and Smeers (2005). The authors look at a simplified one node electricity market featuring two players, one being the peak-load and the other the base-load producer. The authors provide conditions for divergence of open-loop and closed-loop model results and give existence and uniqueness criteria for the closed-loop model. Further, they show that investments and supplies may be larger in the closed-loop model compared to the open-loop model, leading to higher overall welfare in the closed-loop model.

A further line of research in this area is provided by Wogrin et al. (2013b), which provides criteria for open-loop and closed-loop investment models to coincide showing results in the spirit of Kreps and Scheinkmann (1983). Further, in Wogrin et al. (2013a), the authors introduce mathematical programming solution methods to this type of model for a one-node electricity market.

The above analyses only considered the case of one demand region. Lorenczik et al. (2014) were the first to extend the oligopolistic capacity expansion model to a spatial setting. In an application to the coking coal market, the authors model several demand and supply nodes, considering also existing capacities available to the players. The authors show that in a spatial application with non-generic data and existing capacities available to the players, equilibria are likely to deviate between the two modeling approaches. They also provide a quantification of the magnitude of the divergence between closed-loop and open-loop model results with the difference being rather small for welfare, but not for investments and supplies.

Despite the contribution of Lorenczik et al. (2014), until now a systematic analytical treatment for the spatial capacity investment problem is lacking. This paper attempts to close in part this research gap by presenting an extension of the analysis presented in Murphy and Smeers (2005) to the spatial setting. As in Murphy and Smeers (2005), two players are modeled, one representing a peak-load producer, the other a base-load producer. The analysis is extended from the one demand region case considered in Murphy and Smeers (2005) to the spatial setting of two markets with player specific transportation costs to each market. Further, and again in contrast to Murphy and Smeers (2005), also existing capacities of the players are considered in the model. This extension is particularly valuable as, as shown in the following, existing capacities may be another reason not highlighted before for model results to be different between the two models.

Altogether, the setup may be interpreted as a simple electricity market setting, where the physical constraints on transport flows are approximated by transportation costs. While the rather restrictive assumptions on the players' cost structures, which are tailored to the typical peak-load / base-load producer structure in electricity markets, are probably to narrow to be applied to the important resource market case, the analysis presented here may serve as a starting point for further investigations into resource markets. Further, the setting may be applicable to other markets with pronounced and predictable demand variation.

The analysis shows that the main findings of Murphy and Smeers (2005) can be extended to the spatial setting: First, an existence and uniqueness result for the spatial open-loop model is presented as well as closed-form solutions of the open-loop model can be derived. Second, the paper presents general criteria for model results of the spatial open-loop and closed-loop capacity expansion models to coincide respectively to diverge and identifies overcapacity in the market through existing capacities as a new driver for model results to diverge. Third, the paper provides a comparison of the open-loop and closed-loop model results showing that investments and supplies may be larger in the closed-loop model than in the open-loop model, leading to higher consumer surplus in the closed-loop model in these settings.

The remainder of the paper is structured as follows: Section 3.2 describes the notation used in this paper. Section 3.3 introduces the open-loop model and states the main existence and uniqueness result. Section 3.4 presents the closed-loop model. Section 3.5 provides the main results regarding the comparison of open-loop and closed-loop models. Section 3.6 concludes.

3.2 General framework

A spatial, homogeneous good market consisting of two producers $i = 1,2$ and two demand regions $j = 1,2$ is considered. Producers may own existing production capacity cap_i^0. They decide on both investment in new production capacity y_i as well as on their supplies to the two markets at times $t = 1,...,T$. The supply from producer i to market j at time t is given by $x_{i,j}^t$. Total production of producer i at time t is hence given by $\sum_j x_{i,j}^t$. It is limited by the producer's capacity limit $cap_i^0 + y_i$. Figure 3.1 illustrates the spatial structure of the model.

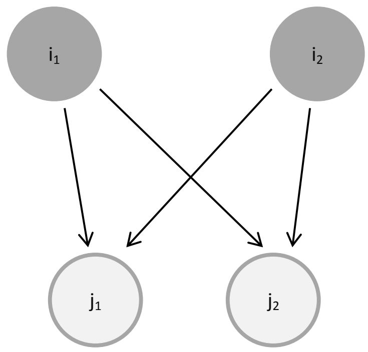


Figure 3.1: Spatial structure of the model: The vertices i_1, i_2 represent the two producers, j_1, j_2 represent the markets. The arrows indicate possible flows from producers to markets.

Investment expenditures for producer i are given by C_i^{inv}. The investment cost function C_i^{inv} is assumed to be linear. With k_i denoting marginal investment costs, it is therefore given by

$$C_i^{inv}(y_i) = k_i \cdot y_i.$$

Newly-built capacity is assumed to produce at the same cost as existing capacity. The variable cost function $C_i^{var,t}$ is assumed to be linear. Variable costs are composed of transportation costs $\tau_{i,j}$ per unit delivered from producer i to market j as well as variable production costs v_i. Both transportation costs and variable production costs are assumed to be time independent. Total variable costs of producer i at time t therefore amount to

$$C_i^{var,t}(\mathbf{x}_i^t) = \sum_j x_{i,j}^t \cdot (\tau_{i,j} + v_i) = \sum_j x_{i,j}^t \cdot \delta_{i,j},$$

with $\mathbf{x}_i^t = (x_{i,j}^t)_j$ denoting the production vector of producer i at time t.

Market prices P_j^t in market j at time t are given by a linear inverse demand function, i.e.,

$$P_j^t = a_j^t - b \cdot \sum_i x_{i,j}^t.$$

with the slope b being independent of time and the same for both markets.

Producers are assumed to maximize profits. Depending on the assumed time and information structure, different model types arise:

- If investment and supply decisions are taken at the same time, an open-loop game with capacity investments is obtained. This type of model is introduced in Section 3.3 and can basically be solved via the KKT conditions of the players' optimization problems. The model can be interpreted as representing a market organized around long-term contracts.
- If investment and supply decisions are taken successively in time, a closed-loop model is obtained. This model type is introduced in Section 3.4 and can be interpreted as representing a market organized around spot markets.

The relation of the closed-loop and the corresponding open-loop problem is at the core of the analysis presented in Section 3.5. In order to facilitate the analysis, more structure is added to the model, namely an extension of the base/peak producer cost structure introduced in Murphy and Smeers (2005) is assumed in the following. In this set-up, one producer, the base-load producer (denoted with subscript b) has a supply cost advantage but an investment cost disadvantage compared to the other producer, the peak-load producer (denoted with subscript p), i.e.,

$$\begin{aligned} x_{\text{low}}(j) \cdot \delta_{p,j} + K_p &< x_{\text{low}}(j) \cdot \delta_{b,j} + K_b \text{ and} \\ x_{\text{high}}(j) \cdot \delta_{b,j} + K_b &< x_{\text{high}}(j) \cdot \delta_{p,j} + K_p \end{aligned}$$

for levels of supply $x_{\text{low}}(j) < \text{LEVEL}(j) < x_{\text{high}}(j)$ and a supply threshold LEVEL(j).

This additional structure enables and facilitates the proofs in Section 3.5. It allows to characterize when model results coincide respectively diverge between the two models as well as to rank model results with respect to investment and supplies. The structure fits well for one important market class, electricity markets. However, adding this structure also comes at a price as for several important markets these assumptions might not be appropriate, like for resource markets.

3.3 The open-loop Cournot model: Simultaneous investment and supply decisions

In the open-loop Cournot model, producers simultaneously make their investment and supply decision with the objective to maximize profits. In doing so, producers take into account their capacity restrictions and their influence on price. In the Cournot case considered here, the influence on price is given by $\frac{\partial P_j^t}{\partial x_{i,j}^t} = b$ for all i. Producer i solves the optimization problem

$$\max_{\mathbf{x}_i^t, y_i} \Big[\sum_t \sum_{j \in J} P_j^t \cdot x_{i,j}^t - \sum_t C_i^{var,t}(\mathbf{x}_i^t) - C_i^{inv}(y_i)\Big]$$

subject to

$$\begin{aligned}
&P_j^t = a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t),\ \forall j, t \\
&cap_i^0 + y_i - \sum_j x_{i,j}^t \geq 0,\ \forall t\ (\lambda_i^t) \\
&x_{i,j}^t \geq 0,\ \forall j \\
&y_i \geq 0.
\end{aligned}$$

Note that producer i assumes in his optimization the supplies $x_{-i,j}^t$ of the other producer as given. The dual variable to the firm's capacity constraint is given by λ_i^t.

Any solution to the above optimization problem satisfies the short-term Karush-Kuhn-Tucker (KKT) conditions

$$\begin{aligned}
&0 \leq \delta_{i,j} - [a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t)] + b \cdot x_{i,j}^t + \lambda_i^t \perp x_{i,j}^t \geq 0,\ \forall j, t \\
&0 \leq cap_i^0 + y_i - \sum_j x_{i,j}^t \perp \lambda_i^t \geq 0,\ \forall t
\end{aligned}$$

as well as the long-term KKT condition

$$0 \leq k_i - \sum_t \lambda_i^t \perp y_i \geq 0.$$

In equilibrium, the KKT conditions for both players have to hold simultaneously. Existence and uniqueness of the open-loop Cournot equilibrium can be proven using the theory of variational inequalities (see Harker and Pang, 1990, for an overview of the theory of variational inequalities).

Theorem 3.1. *There exists an open-loop Cournot equilibrium and it is unique.*

Proof. See Appendix B.1. □

Note that the KKT conditions are necessary and sufficient to solve the open-loop Cournot model due to the quasi-concave objective function and the convexity of the restrictions. Apart from the general existence and uniqueness result presented in Theorem 3.1, in the present context it is possible to derive the closed-form solution of the open-loop Cournot model. This is done in Appendix B.1 for the one-period case and a sketch is provided of the derivation in the multi-period case.[13]

3.4 The closed-loop Cournot model: Successive investment and supply decisions

In the closed-loop Cournot model, producers play a two-stage game. The timing is as follows:

- In the first stage, producers simultaneously decide on their investments.
- In the second stage, producers choose their production and supplies, based on *observed* investment decisions of the first stage.

This structure can be interpreted as a market organized along spot markets. An equilibrium to this problem is subgame perfect and solving the model leads into the class of EPECs, see e.g. the overviews presented in Ehrenmann (2004) or Gabriel et al. (2012) for a general introduction to EPECs. The model is solved by backward induction, i.e., by first solving for the optimal solution of the second stage, the short-run problem.

3.4.1 The short-run problem

For a given investment vector $y = (y_i, y_{-i})$, the short-run problem of producer i is given by

$$\max_{\mathbf{x}_i^t} \left[\sum_t \sum_{j \in J} P_j^t \cdot x_{i,j}^t - \sum_t C_i^{var,t}(\mathbf{x}_i^t)\right]$$

subject to

$$\begin{aligned}
&P_j^t = a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t), \ \forall j, t \\
&cap_i^0 + y_i - \sum_j x_{i,j}^t \geq 0, \ (\lambda_i^t) \\
&x_{i,j}^t \geq 0, \ \forall j.
\end{aligned}$$

[13]Note that the existence and uniqueness result holds under much weaker assumptions than the peak-load / base-load producer setting analyzed here.

In the short-run problem, producer i decides on his production and supplies while taking the decisions of the other producer as given. Producer i also takes his capacity constraint into account, the dual variable of which is given by λ_i^t. Further, Cournot behavior is assumed. The corresponding KKT conditions to this problem are then given by

$$
\begin{aligned}
&0 \leq \delta_{i,j} - [a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t)] + b \cdot x_{i,j}^t + \lambda_i^t \perp x_{i,j}^t \geq 0, \ \forall j, t \\
&0 \leq cap_i^0 + y_i - \sum_j x_{i,j}^t \perp \lambda_i^t \geq 0, \ \forall t.
\end{aligned}
$$

In the short-run equilibrium, the KKT conditions of both players have to hold simultaneously. Let $x_{i,j}^t(y)$ or $x_{i,j}^t(y_i, y_{-i})$ denote the short-run equilibrium for a given investment vector $y = (y_i, y_{-i})$.

Lemma 3.2 provides a characterization of the short-run equilibrium. Note, however that short-run equilibrium curve is typically non-differentiable and has jump points. This feature was explored in detail in Murphy and Smeers (2005) for the one demand node case and also applies to the two demand node case considered here. The further analysis will abstract from these issues of differentiability.

Lemma 3.2. *$x_{i,j}^t(y_i, y_{-i})$ is unique for given (y_i, y_{-i}) as well as left and right differentiable with respect to $y_k, k = i, -i$.*

Proof. See Appendix B.2. □

3.4.2 The long-run problem

In the first stage of the closed-loop problem, the long-run problem, producer i chooses his investment in order to maximize profits for a given investment strategy of the other producer (y_{-i}) under consideration of the resulting short-run equilibrium. The long-run problem for producer i can be stated as

$$
\max_{y_i} \big[\sum_t \sum_{j \in J} P_j^t \cdot x_{i,j}^t(y_i, y_{-i}) - \sum_t C_i^{var,t}(\mathbf{x}_i^t(y_i, y_{-i})) - C_i^{inv}(y_i) \big]
$$

subject to

$$
\begin{aligned}
&P_j^t = a_j^t - b \cdot [x_{i,j}^t(y_i, y_{-i}) + x_{-i,j}^t(y_i, y_{-i})], \ \forall j, t \\
&y_i \geq 0.
\end{aligned}
$$

Combining the short-run and the long-run problem, the following MPEC for producer i is obtained, hereafter referred to as MPEC$_i$:

$$\max_{\Omega_i} \big[\sum_t \sum_{j \in J} P_j^t \cdot x_{i,j}^t - \sum_t C_i^{var,t}(\mathbf{x}_i^t) - C_i^{inv}(y_i)\big]$$

subject to

$$\begin{aligned}
&y_i \geq 0,\\
&P_j^t = a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t), \ \forall j,t\\
&0 \leq \delta_{k,j} - [a_j^t - b \cdot (x_{k,j}^t + x_{-k,j}^t)] + b \cdot x_{k,j}^t + \lambda_k^t \perp x_{k,j}^t \geq 0, \ \forall j,t \text{ and } k = i, -i\\
&0 \leq cap_k^0 + y_k - \sum_j x_{k,j}^t \perp \lambda_k^t \geq 0, \ \forall t \text{ and } k = i, -i.
\end{aligned}$$

Producer i considers the investment y_{-i} of the other producer as given and optimizes over the choice set $\Omega_i = \{y_i; (x_{k,j}^t, \lambda_k^t)_{k,j,t}\}$. The first stage decision variable is separated from the second stage (decision and dual) variables by a semicolon as the latter are indirectly determined by the first stage choices.

Definition 3.3. An investment strategy $(\tilde{y}_i, \tilde{y}_{-i})$ is a closed-loop equilibrium if for all i, $\tilde{y}_i$ solves i's MPEC problem MPEC$_i$ given $\tilde{y}_{-i}$.

The problem of finding a closed-loop equilibrium is hence of EPEC type in the sense of Gabriel et al. (2012).

3.5 Comparing the open-loop and the closed-loop investment model

In order to compare the open-loop and closed-loop model solutions, properties of the short run curve $x_{i,j}^t(y)$ for a given time point t are analyzed. The following cases, disregarding some of the symmetric cases, can be distinguished:

1. Both players produce and supply both markets, i.e., $x_{i,j}^t > 0$ for all i, j
2. Player 1 supplies both markets, player 2 only market 1, i.e., $x_{1,1}^t > 0$, $x_{1,2}^t > 0$, $x_{2,1}^t > 0$ and $x_{2,2}^t = 0$
3. Player 1 supplies both markets, player 2 none, i.e., $x_{1,1}^t > 0$, $x_{1,2}^t > 0$, $x_{2,1}^t = 0$ and $x_{2,2}^t = 0$

4. Player 1 supplies market 1, player 2 supplies market 2, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} = 0$, $x^t_{2,1} = 0$ and $x^t_{2,2} > 0$

5. Player 1 supplies market 1, player 2 does not supply, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} = 0$, $x^t_{2,1} = 0$ and $x^t_{2,2} = 0$

Each of the cases has the following sub-cases, the composite cases are referred to in the obvious way by (1a) to (5d).

(a) Both players produce at full capacity

(b) Both players do not produce at full capacity

(c) Player 1 produces at full capacity, player 2 does not

(d) Player 1 does not produce at full capacity, player 2 does

In the further analysis, a different characterization of the solution to the closed-loop problem is used. For this, let $B_u x^t_{i,j}(y) = \frac{\partial x^t_{i,j}(y)}{\partial y_u}$, $u = 1, 2$. A closed-loop solution then satisfies, abstracting from the problems of differentiability of the short run equilibrium curve alluded to in the previous section,

$$\begin{aligned} 0 \leq -\sum_t \sum_{j \in J} [a^t_j - 2bx^t_{i,j}(y) - bx^t_{-i,j}(y) - \delta^t_{i,j}] \cdot B_i x^t_{i,j}(y) \\ + \sum_t \sum_{j \in J} bx^t_{i,j}(y) \cdot B_i x^t_{-i,j}(y) + K_i \perp y_i \geq 0. \end{aligned} \tag{3.1}$$

The following lemma characterizes $B_u x^t_{i,j}(y)$.

Lemma 3.4. *For the cases described above it holds:*

1. *All produce and supply both markets*

(1a) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $B_2 x^t_{1,j}(y) = 0$
$\sum_j B_2 x^t_{2,j}(y) = 1$ *and* $B_1 x^t_{2,j}(y) = 0$

(1b) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
$B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

(1c) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $\sum_j B_2 x^t_{1,j}(y) = 0$
$B_2 x^t_{2,j}(y) = 0$ *and* $\sum_j B_1 x^t_{2,j}(y) = -0.5$

(1d) $B_1 x^t_{1,j}(y) = 0$ *and* $\sum_j B_2 x^t_{1,j}(y) = -0.5$
$\sum_j B_2 x^t_{2,j}(y) = 1$ *and* $\sum_j B_1 x^t_{2,j}(y) = 0$

2. *Player 1 supplies both markets, player 2 only market 1*

   (2a) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,1}(y) = 1$ *and* $B_1 x^t_{2,1}(y) = 0$
   $B_2 x^t_{2,2}(y) = 0$ *and* $B_1 x^t_{2,2}(y) = 0$

   (2b) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (2c) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $\sum_j B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,1}(y) = 0$ *and* $B_1 x^t_{2,1}(y) = -0.5 B_1 x^t_{1,1}$
   $B_2 x^t_{2,2}(y) = 0$ *and* $B_1 x^t_{2,2}(y) = 0$

   (2d) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,1}(y) = -0.5$ *and* $B_2 x^t_{1,2}(y) = 0$
   $B_2 x^t_{2,1}(y) = 1$ *and* $B_1 x^t_{2,1}(y) = 0$
   $B_2 x^t_{2,2}(y) = 0$ *and* $B_1 x^t_{2,2}(y) = 0$

3. *Player 1 supplies both markets, player 2 none*

   (3a) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (3b) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (3c) $\sum_j B_1 x^t_{1,j}(y) = 1$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (3d) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

4. *Player 1 supplies market 1, player 2 supplies market 2*

   (4a) $B_1 x^t_{1,1}(y) = 1$ *and* $B_2 x^t_{1,1}(y) = 0$
   $B_1 x^t_{1,2}(y) = 0$ *and* $B_2 x^t_{1,2}(y) = 0$
   $B_2 x^t_{2,2}(y) = 1$ *and* $B_1 x^t_{2,2}(y) = 0$
   $B_2 x^t_{2,1}(y) = 0$ *and* $B_1 x^t_{2,1}(y) = 0$

   (4b) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (4c) $B_1 x^t_{1,1}(y) = 1$ *and* $B_2 x^t_{1,1}(y) = 0$
   $B_1 x^t_{1,2}(y) = 0$ *and* $B_2 x^t_{1,2}(y) = 0$
   $B_2 x^t_{2,j}(y) = 0$ *and* $B_1 x^t_{2,j}(y) = 0$

   (4d) $B_1 x^t_{1,j}(y) = 0$ *and* $B_2 x^t_{1,j}(y) = 0$
   $B_2 x^t_{2,2}(y) = 1$ *and* $B_1 x^t_{2,2}(y) = 0$
   $B_2 x^t_{2,1}(y) = 0$ *and* $B_1 x^t_{2,1}(y) = 0$

5. *Player 1 supplies market 1, player 2 none*

(5a) $B_1 x_{1,1}^t(y) = 1$ *and* $B_2 x_{1,1}^t(y) = 0$
$B_2 x_{1,1}^t(y) = 0$ *and* $B_1 x_{1,2}^t(y) = 0$
$B_2 x_{2,j}^t(y) = 0$ *and* $B_1 x_{2,2}^t(y) = 0$

(5b) $B_1 x_{1,j}^t(y) = 0$ *and* $B_2 x_{1,j}^t(y) = 0$
$B_2 x_{2,j}^t(y) = 0$ *and* $B_1 x_{2,j}^t(y) = 0$

(5c) $B_1 x_{1,1}^t(y) = 1$ *and* $B_2 x_{1,1}^t(y) = 0$
$B_2 x_{1,1}^t(y) = 0$ *and* $B_1 x_{1,2}^t(y) = 0$
$B_2 x_{2,j}^t(y) = 0$ *and* $B_1 x_{2,2}^t(y) = 0$

(5d) $B_1 x_{1,j}^t(y) = 0$ *and* $B_2 x_{1,j}^t(y) = 0$
$B_2 x_{2,j}^t(y) = 0$ *and* $B_1 x_{2,j}^t(y) = 0$

Proof. See Appendix B.2. □

It is easy to see that when there are time points of type (2c) or (2d), then it is the peak player that is not supplying to one market. This distinction can only be made due to the special cost structure assumptions made on the players. From this and Lemma 3.4, the two main relations, summarized in the following theorem, between closed-loop and open-loop solutions are derived. The theorem shows that the existence of time points of types (1c), (1d), (2c) or (2d) leads to the solutions of the two model types to fall apart. If not present, the two model results coincide. The theorem illustrates that the solutions basically fall apart when one player can influence the decisions of the other player through his own actions. Note that the cases (1c), (1d), (2c) or (2d) also include the interesting case of markets with overcapacity. With one player having existing overcapacity, open-loop and closed-loop model results may fall apart.

Theorem 3.5. *a) When there is no time point of the closed-loop equilibrium of types (1c), (1d), (2c) or (2d), then the closed-loop equilibrium is the same as the corresponding open-loop equilibrium.*

b) When there is a time point of the closed-loop equilibrium of types (1c), (1d), (2c) or (2d), then the closed-loop equilibrium is different from the corresponding open-loop equilibrium.

Proof. Proof of part a): Applying Lemma 3.4 to Equation (3.1) it follows that

$$\begin{aligned}
0 &= -\sum_t \sum_{j\in J} [a_j^t - 2bx_{i,j}^t(y) - bx_{-i,j}^t(y) - \delta_{i,j}^t] \cdot B_i x_{i,j}^t(y) \\
&+ \sum_t \sum_{j\in J} bx_{i,j}^t(y) \cdot \underbrace{B_i x_{-i,j}^t(y)}_{=0} + K_i \\
&= -\sum_t \sum_{j\in J} \underbrace{[a_j^t - 2bx_{i,j}^t(y) - bx_{-i,j}^t(y) - \delta_{i,j}^t]}_{\lambda_i^t} \cdot B_i x_{i,j}^t(y) + K_i \\
&= -\sum_t \lambda_i^t \sum_{j\in J} B_i x_{i,j}^t(y) + K_i \\
&= -\sum_t \lambda_i^t + K_i
\end{aligned}$$

which shows that the closed-loop equilibrium is the same as the corresponding open-loop equilibrium.

Proof of part b): Applying Lemma 3.4 to Equation (3.1), it holds for the player whose capacity is not fully used

$$\begin{aligned}
0 &= -\sum_t \lambda_{i,j}^t + K_i + \sum_{t\in(1c),(1d),(2c) \text{ or } (2d)} \underbrace{\sum_{j\in J} bx_{i,j}^t(y) \cdot B_i x_{-i,j}^t(y)}_{<0} \\
&< -\sum_t \lambda_i^t + K_i
\end{aligned}$$

which shows that the solutions fall apart. Similar reasoning applies for the other cases. □

It further holds for both the open-loop and the closed-loop model that if the capacity is binding for the peak player, it is also be binding for the base player. From this it follows that for the closed-loop equilibrium

$$K_b > \sum_t \lambda_b^t \text{ and } K_p = \sum_t \lambda_p^t$$

if there are time points of types (1c), (1d), (2c) or (2d). This relationship will be key input in proving the following theorem comparing capacity investment in the open-loop and closed-loop model, which shows that the existence of time points of types (1c), (1d), (2c) or (2d) leads to investments being larger in the closed-loop model than in the open-loop model. Moreover, in this case it holds that it is the base player who might invest more in the closed-loop model and that overall supply is larger. In the case of symmetric markets, consumer welfare is larger in the closed-loop model.

Theorem 3.6. *a) The capacity investment in a closed-loop equilibrium is at least as large as the capacity investment in the corresponding open-loop equilibrium. It is larger when there are time points of types (1c), (1d), (2c) or (2d).*

b) The base capacity investment in the closed-loop equilibrium is at least as large as in the open-loop equilibrium.

c) The supplies in the closed-loop model are at least as large as the supplies in the open-loop model.

d) In case of symmetric markets, i.e., $a_j = a$*, overall consumer welfare in the closed-loop model is at least as large as in the open-loop model.*

Proof. Proof of part a): Let the superscripts c and o stand for the closed-loop and open-loop equilibrium. The theorem is proven by contradiction distinguishing two cases.
Case 1: Suppose that $y_b^o + y_p^o > y_b^c + y_p^c$ and $y_p^o > y_p^c$. It suffices to show that $\sum_t \lambda_p^{t,c} > K_p$, which yields the desired contradiction.
The long-term open-loop equilibrium condition yields $\sum_t \lambda_p^{t,o} = K_p$. It remains to be shown that $\lambda_p^{t,c} > \lambda_p^{t,0}$ for some t. For this let $\lambda_p^{t,o} > 0$ for some t. This implies

$$\sum_j x_{p,j}^{t,o} - cap_p^0 = y_p^o > y_p^c \geq \sum_j x_{p,j}^{t,c} - cap_p^0. \tag{3.2}$$

Further, since the peak capacity is binding, also the base capacity is binding, i.e.,

$$\sum_j x_{b,j}^{t,o} - cap_b^0 = y_b^o.$$

Combining these two relations it follows

$$\sum_j x_{p,j}^{t,o} - cap_p^0 + \sum_j x_{b,j}^{t,o} - cap_b^0 = y_p^o + y_b^o > y_p^c + y_b^c \geq \sum_j x_{p,j}^{t,c} - cap_p^0 + \sum_j x_{b,j}^{t,c} - cap_b^0. \tag{3.3}$$

Adding Equations (3.2) and (3.3) and simplifying, it follows that

$$2\sum_j x_{p,j}^{t,o} + \sum_j x_{b,j}^{t,o} > 2\sum_j x_{p,j}^{t,c} + \sum_j x_{b,j}^{t,c}$$

from which

$$\lambda_p^{t,c} > \lambda_p^{t,o}$$

and hence the desired contradiction follows.
Case 2: Suppose that $y_b^o + y_p^o > y_b^c + y_p^c$ and $y_b^o > y_b^c$. It suffices to show that $\sum_t \lambda_b^{t,c} > K_b$, which yields the desired contradiction.
The long-term open-loop equilibrium condition yields $\sum_t \lambda_b^{t,o} = K_b$. It remains to be

shown that $\lambda_b^{t,c} > \lambda_b^{t,o}$ for some t. For this let $\lambda_b^{t,o} > 0$. From this it follows

$$\sum_j x_{b,j}^{t,o} - cap_b^0 = y_b^o > y_b^c \geq \sum_j x_{b,j}^{t,c} - cap_b^0. \tag{3.4}$$

Case 2.1: Let $\lambda_p^{t,o} > 0$. This implies

$$\sum_j x_{p,j}^{t,o} - cap_p^0 = y_p^o.$$

Adding this to Equation (3.4) it follows

$$\sum_j x_{p,j}^{t,o} - cap_p^0 + \sum_j x_{b,j}^{t,o} - cap_b^0 = y_p^o + y_b^o > y_p^c + y_b^c \geq \sum_j x_{p,j}^{t,c} - cap_p^0 + \sum_j x_{b,j}^{t,c} - cap_b^0. \tag{3.5}$$

Adding Equations (3.4) and (3.5) and simplifying as above, the desired result again follows.
Case 2.2: Let $\lambda_p^{t,o} = 0$. Adding the short-run open-loop equilibrium conditions for the peak player, it follows

$$\sum_j \delta_{p,j}^t - \sum_j a_j^t + 2b \sum_j x_{p,j}^{t,o} + b \sum_j x_{b,j}^{t,o} = 0$$

and for the closed-loop equilibrium

$$\sum_j \delta_{p,j}^t - \sum_j a_j^t + 2b \sum_j x_{p,j}^{t,c} + b \sum_j x_{b,j}^{t,c} + 2\lambda_p^{t,c} = 0.$$

From this, it can be concluded that

$$\begin{aligned}
2b \sum_j x_{p,j}^{t,o} + b \sum_j x_{b,j}^{t,o} &= -\sum_j \delta_{p,j}^t + \sum_j a_j^t \\
&\geq -\sum_j \delta_{p,j}^t + \sum_j a_j^t - 2\lambda_p^{t,c} \\
&= 2b \sum_j x_{p,j}^{t,c} + b \sum_j x_{b,j}^{t,c}.
\end{aligned} \tag{3.6}$$

Adding Equation (3.4) multiplied by $3b$ and Equation (3.6) and simplifying the desired contradiction follows.

Proof of part b): Suppose that $y_p^o < y_p^c$. Together with $y_p^o + y_b^o < y_p^c + y_b^c$ it follows $2y_p^o + y_b^o < 2y_p^c + y_b^c$. Let $K_p = \sum_{t'} \lambda_p^{t',c} + \sum_{t''} \lambda_p^{t'',c}$ where $\lambda_p^{t',c} > 0$ and $\lambda_p^{t'',c} = 0$. Since $\lambda_p^{t',c} > 0$ implies $\lambda_b^{t',c} > 0$, it holds that

$$2\sum_j x_{p,j}^{t',o} - 2cap_p^0 + \sum_j x_{b,j}^{t',o} - cap_b^0 \leq 2y_p^o + y_b^o < 2y_p^c + y_b^c = 2\sum_j x_{p,j}^{t',c} - 2cap_p^0 + \sum_j x_{b,j}^{t',c} - cap_b^0$$

from which $\lambda_p^{t',o} > \lambda_p^{t',c}$ follows. Therefore,

$$K_p = \sum_{t'} \lambda_p^{t',c} + \sum_{t''} \lambda_p^{t'',c} < \sum_{t'} \lambda_p^{t',o} + \sum_{t''} \lambda_p^{t'',o} = K_p,$$

a contradiction. Proof of part c): It holds that $y_b^o \leq y_b^c$ and $y_p^o + y_b^o < y_p^c + y_b^c$.

Case 1: Suppose that $\lambda_p^{t,c} > 0$. Then $\lambda_b^{t,c} > 0$ and

$$\sum_j x_{p,j}^{t,o} + \sum_j x_{b,j}^{t,o} \leq cap_p^0 + y_p^o + cap_b^0 + y_b^o < cap_p^0 + y_p^c + cap_b^0 + y_b^c = \sum_j x_{p,j}^{t,c} + \sum_j x_{b,j}^{t,c}$$

from which the result follows.

Case 2: Suppose now that $\lambda_p^{t,c} = 0$ and $\lambda_b^{t,c} > 0$. It then holds at $(x_p^{t,c}, y_b^c)$

$$\sum_j \delta_{p,j}^t - \sum_j a_j^t + 2b \sum_j x_{p,j}^t + b(cap_b^0 + y_b) = 0 \quad (3.7)$$

$$\sum_j \delta_{b,j}^t - \sum_j a_j^t + b \sum_j x_{p,j}^t + 2b(cap_b^0 + y_b) + 2\lambda_b^s = 0. \quad (3.8)$$

Taking the derivative with respect to y_b, it follows that $\sum_j x_{p,j}^t + cap_b^0 + y_b$ decreases as y_b decreases while both conditions (3.7) and (3.8) continue to hold. From this the claim follows by distinguishing cases of the decrease of y_b from y_b^c towards y_b^o.

Proof of part d): The claim follows readily by adding up the two consumer surpluses of the markets. □

3.6 Conclusions

This paper presents two models of capacity investments in spatial markets. The first model, the open-loop Cournot model, assumes that players decide simultaneously on investments and supplies. The second-model, the closed-loop Cournot model assumes that supply decisions are made based on observed prior investment decisions. Both models have real world interpretations; whereas the first model represents markets organized along long-term contracts, the second model represents markets organized along spot markets. This dichotomy between the two market structures is particularly apparent in resource and electricity markets in which recently a shift away from long-term to more spot-market based trading has been observed and a mix of differently traded products exists.

In a simple electricity market setting several results are obtained: First, an existence and uniqueness result for the open-loop case is derived. Second, the paper provides a comparison of open-loop and closed-loop model results presenting criteria for the results of the two models to coincide respectively to diverge. The analysis shows the important role of existing capacities in the model and the role they play for market outcomes to coincide or diverge. And third, the paper shows that supplies and investments in the closed-loop model may be larger than in the open-loop model under certain assumptions regarding cost and demand structure, resulting in higher consumer welfare in the closed-loop model in these cases.

Several promising research streams may be conducted based on the findings presented here. First, further research needs to be directed towards investigating existence and uniqueness in closed-loop capacity investment models. Previous analysis has shown that in other closed-loop settings existence and uniqueness is highly parameter dependent and moreover pure strategy equilibria may not exist. Second, also regarding effective empirical programing and solution techniques more work needs to be conducted. Up to now, only relatively small-scale closed-loop models have been solved successfully empirically. Scaling these techniques up to generate effective solution strategies also for larger models would be a significant contribution. Third, the cost and demand structure in the analysis presented here is just one relevant case, particularly suited for electricity market applications. More general cost and demand structures might need to be considered for the important class of resource market applications.

Chapter 4

Modeling strategic investment decisions in spatial markets

Markets for natural resources and commodities are often oligopolistic. In these markets, production capacities are key for strategic interaction between the oligopolists. We analyze how different market structures influence oligopolistic capacity investments and thereby affect supply, prices and rents in spatial natural resource markets using mathematical programing models. The models comprise an investment period and a supply period in which players compete in quantities. We compare three models, a perfect competition and two Cournot models, in which the product is either traded through long-term contracts or on spot markets in the supply period. Tractability and practicality of the approach are demonstrated in an application to the international metallurgical coal market. Results may vary substantially between the different models. The metallurgical coal market has recently made progress in moving away from long-term contracts and more towards spot market-based trade. Based on our results, we conclude that this regime switch is likely to raise consumer rents but lower producer rents, while the effect on total welfare is negligible.

4.1 Introduction

Markets for natural resources and commodities such as iron ore, copper ore, coal, oil or gas are often highly concentrated and do not appear to be competitively organized at first glance. In such markets, large companies run mines, rigs or gas wells and trade their product globally. In the short term, marginal production costs and capacities are given and determine the companies' competitive position in the oligopolistic market.

However, in the longer term, companies can choose their capacity and consequently alter their competitive position.

Investing in production capacity is a key managerial challenge and determining the right amount of capacity is rarely trivial in oligopolistic markets. Suppliers have to take competitors' reactions into account not only when deciding on the best supply level but also when choosing the best amount of capacity.

In this paper, we introduce three different models to address this capacity expansion problem in oligopolistic natural resource markets under varying assumptions of market structure and conduct. Moreover, we pursue the question as to how different market structures influence capacity investments, supply, prices and rents. The models comprise two periods: an investment period and a supply period in which players compete in quantities. We explicitly account for the spatial structure of natural resource markets, i.e., demand and supply regions are geographically separated and market participants incur distance-dependent transportation costs.

The first model assumes markets to be contestable; hence investment follows competitive logic. Solving this model yields the same result as would be given by a perfectly competitive market. The second model assumes the product to be sold through long-term contracts under imperfect competition. Even though supply takes place in period two, the supply and investment decisions are made simultaneously in period one. The long-term contract that is fulfilled in period two determines the level of capacity investment in period one. Any production capacity that is different from the one needed to produce the quantity of the best-supply equilibrium in period two reduces the respective players profits and is not a Nash equilibrium. The outcome is termed 'open-loop Cournot equilibrium' and corresponds to the result of a static one-period Cournot game (accounting for investment costs). The third model assumes that investment and supply decisions are made consecutively: In period one, when investment takes place, none of the oligopolists can commit to their future output decision in period two (unlike in the open-loop case). In period two, when the market clears, the investment cost spent in the first period is sunk and the players base their output decision solely on production cost. The resulting equilibrium is termed 'closed-loop Cournot equilibrium' and may differ from the open-loop outcome.

Intuitively, the lack of commitment in the closed-loop game and therefore the repeated interaction of the oligopolists would suggest a higher degree of competition and thus lower prices and higher market volumes than in the open-loop equilibrium. However, the players anticipate this strategic effect and make their investment decisions accordingly. How prices and volumes rank compared to the open-loop game is parameter-dependent and requires a numerical analysis. As discussed for instance in Fudenberg and Tirole

(1991) in a more general context, each player in the closed-loop model has a strategic incentive to deviate from his first period open-loop action as he can thereby influence the other players' second period action. Applying this general economic framework to the capacity expansion problem examined in this paper, indeed tends to lead to higher investment and supply levels in the closed-loop model and hence to lower prices.

Computing open-loop games is relatively well understood, and existence and uniqueness of the equilibrium can be guaranteed under certain conditions (see, e.g., Harker, 1984, 1986, Takayama and Judge, 1964, 1971). The open-loop Cournot model can be solved via the Karush-Kuhn-Tucker conditions as a mixed complementarity problem (MCP). Oligopolistic spatial equilibrium models have been widely deployed in analyzing resource markets, without taking investments decisions into account, e.g., for steam coal markets (Haftendorn and Holz, 2010, Kolstad and Abbey, 1984, Trüby and Paulus, 2012), metallurgical coal markets (Graham et al., 1999, Trüby, 2013), natural gas markets (Gabriel et al., 2005, Growitsch et al., 2013, Holz et al., 2008, Zhuang and Gabriel, 2008), wheat markets (Kolstad and Burris, 1986), oil markets (Huppmann and Holz, 2012) or for iron ore markets (Hecking and Panke, 2014). Investments in additional production capacity have been analyzed for example in Huppmann (2013) with investment and production decisions being made simultaneously and therefore implicitly assuming a market structure with long-term contracts.

Closed-loop models are computationally challenging due to their non-linear nature. Depending on the problem this can be resolved. Gabriel and Leuthold (2010) for instance model an electricity market with a Stackelberg leader using linearization to guarantee a globally optimal solution. Closed-loop models in energy market analysis have primarily been used to study restructured electricity markets (e.g., Daxhelet and Smeers, 2007, Shanbhag et al., 2011, Yao et al., 2008, 2007). Murphy and Smeers (2005) and Wogrin et al. (2013a,b) have analyzed the implications of closed- and open-loop modeling on market output and social welfare as well as characterized conditions under which closed- and open-loop model results coincide.

Our two-stage model consists of multiple players on both, the first and second stage (investment in period one and supply in period two), and therefore existence and uniqueness of (pure strategy) equilibria cannot be guaranteed. The closed-loop model, which is formulated as an Equilibrium Problem with Equilibrium Constraints (EPEC), is implemented using a diagonalization approach (see, e.g., Gabriel et al., 2012). In doing so, we reduce the solution of the EPEC to the solution of a series of Mathematical Programs with Equilibrium Constraints (MPEC). Concerning the solution of the MPECs we implement two algorithms, grid search along the investment decisions of the individual players and a Mixed Integer Linear Program reformulation following Wogrin et al. (2013a).

We demonstrate the tractability and practicality of our investment models in an application to the international metallurgical (or coking) coal trade. Metallurgical coal is, due to its special chemical properties, a key input in the process of steel-making. The market for this rare coal variety is characterized by a spatial oligopoly with producers mainly located in Australia, the United States and Canada competing against each other and providing the bulk of the traded coal (Bowden, 2012, Trüby, 2013). The players hold existing mining capacity and can invest into new capacity. Investment and mining costs differ regionally. Key uncertainties in this market are demand evolution and price responsiveness of demand. We therefore compute sensitivities for these parameters to demonstrate the robustness of our results.

Our findings are generally in line with previous results found in the literature on two-period games with players choosing capacity and output, i.e., we find that prices and supply levels in the closed-loop game fall between those in the perfect competition and the open-loop game (see, e.g., Murphy and Smeers, 2005). If investment costs are low compared to variable costs of supply, the strategic effect of the two-stage optimization in the closed-loop game diminishes. With investment costs approaching zero, the closed-loop result converges to the open-loop result. Hence, the closed-loop model is particularly useful for capital-intensive natural resource industries in which the product is traded on spot markets.

The numerical results for supply levels, prices and rents in the metallurgical coal market analysis differ markedly between the three models. Consistent with actual industry investment pipelines, our model suggests that the bulk of the future capacity investment comes from companies operating in Australia followed by Canadian and US firms. Starting in 2010, the metallurgical coal market has undergone a paradigm shift, moving away from long-term contracts and more towards a spot market-based trade – with similar tendencies being observed in other commodity markets such as the iron ore trade. In light of our findings, this effect is detrimental to the companies' profits but beneficial to consumer rents. The effect on welfare is negligible: Gains in consumer rents and losses in producers' profits are of almost equal magnitude.

The contribution of this paper is threefold: First, by extending the multi-stage investment approach to the case of spatial markets, we introduce a novel feature to the literature on Cournot capacity expansion games. Second, we outline how our modeling approach can be implemented and solved to analyze capacity investments in natural resource markets. We thereby extend previous research on natural resource markets, which has typically assumed capacities to be given. Finally, we illustrate and discuss the model properties on the basis of a real-world application to the international metallurgical coal trade and draw conclusions for this market. In doing so, we also take into account existing capacities of the players and hence incorporate a feature which to our knowledge has been ignored in previous work on multi-stage Cournot capacity expansion games. By comparing open- and closed-loop model results, we illustrate possible consequences of the ongoing regime switch from long-term contracts to a more spot market-based trade in the international metallurgical coal market. Our analysis in particular allows for the first quantification of the magnitude of the divergence between open- and closed-loop model results in a real-world application.

The remainder of the paper is structured as follows: Section 4.2 describes the models developed in this paper and Section 4.3 provides details about their implementation. The data is outlined in Section 4.4, results are presented in Section 4.5. Section 4.6 discusses computational issues and Section 4.7 concludes.

4.2 The Model

We introduce three different approaches to the capacity expansion problem – two open-loop models and a closed-loop model. In the open-loop models, all players decide simultaneously on their investment *and* production levels, whereas in the closed-loop model all players *first* decide on their *investment* levels simultaneously and *then*, based on observed investment levels, they simultaneously decide on their *production* levels. The two open-loop models vary in their underlying market structure: one model assumes perfect competition, the other model assumes Cournot competition with a competitive fringe. The closed-loop model also assumes Cournot competition with a competitive fringe.

While similar open-loop models have previously been studied, the introduced closed-loop model varies from existing closed-loop models by taking into account also the spatial structure of the market as well as considering existing capacities of the players.

4.2.1 General Setting and Notations

Table 4.1 summarizes the most relevant nomenclature used throughout this section. Additional symbols are explained where necessary. We assume a spatial, homogeneous good market consisting of producers $i \in I$, production facilities $m \in M$ and demand regions $j \in J$. Each producer i owns production facilities $m \in M_i \subset M$. Furthermore, we assume that $M_i \cap M_j = \emptyset$ for $i \neq j$, i.e., production facilities are exclusively owned by one producer. Producers decide on both their investment in production facilities as well as on their supply levels.

As in equilibrium added capacities are fully utilized, no stock constraint for new capacities is modeled. Therefore we implicitly assume that mines will be exhausted after their depreciation period (see Section 4.4).

The supply from production facility m to market j is given by $x_{m,j}$. Total production of production facility m is hence given by $\sum_j x_{m,j}$. It is limited by the facilities' capacity $cap_m^0 + y_m$, where cap_m^0 is the initial production capacity and y_m denotes the capacity investment. Capacity investments y_m are non-negative and limited by y_m^{max}. The upper bound on capacity expansion is chosen sufficiently high not to impose restrictions on economically favorable investments but is rather used to ease the solution algorithm (the upper limit restricts the solution space of the non-linear MPEC and enables the equidistant separation of investments in the case of the line search, see Section 4.3).

Capacity investments in an existing production facility (i.e., $cap_m^0 \neq 0$) can be interpreted as capacity expansions, and investments in the case of $cap_m^0 = 0$ as newly built production facilities.

Investment expenditures for facility m are given by C_m^{inv}. We assume that C_m^{inv} is a linear function in the investment level y_m, with k_m denoting marginal investment costs, i.e.,

$$C_m^{inv}(y_m) = k_m \cdot y_m.$$

Variable costs C_m^{var} are specific to the production facility m. They are composed of transportation costs $\tau_{m,j}$ per unit delivered from m to market j as well as the variable production costs v_m. We assume that v_m is a linear function in the total production of the facility. Total variable costs of facility m therefore amount to

$$C_m^{var}(\mathbf{x}_m) = \sum_j (x_{m,j} \cdot \tau_{m,j}) + v_m(\sum_j x_{m,j}),$$

with $\mathbf{x}_m = (x_{m,j})_j$ denoting the production vector of facility m.

Market prices P_j in market j are given by a linear inverse demand function, i.e.,

$$P_j = a_j - b_j \cdot \sum_m x_{m,j}.$$

Table 4.1: Model sets, parameters and variables

Abbreviation	Description
Model sets	
$m \in M$	Production facilities
$j \in J$	Markets
$i \in I$	Players
Model parameters	
k_m	Marginal investment costs [US$ per unit per year]
v_m	Variable production costs [US$ per unit]
$\tau_{m,j}$	Transportation costs [US$ per unit]
a_j	Reservation price [US$ per unit]
b_j	Linear slope of demand function
cap_m^0	Initial production capacity [units per year]
y_m^{max}	Maximum capacity expansion [units per year]
Model variables	
C_m^{var}	Total variable production costs [US$]
C_m^{inv}	Investment expenditures [US$]
$x_{m,j}$	Supply [units]
P_j	Market price [US$ per unit]
y_m	Capacity investments [units per year]

4.2.2 Model 1: The Open-Loop Perfect Competition Model

In the open-loop perfect competition model (in the following simply termed 'perfect competition model'), each producer $i \in I$ solves the optimization problem

$$\max_{\mathbf{x}_m, y_m : m \in M_i} \sum_{m \in M_i} \big(\sum_{j \in J} P_j \cdot x_{m,j} - C_m^{var}(\mathbf{x}_m) \big) - \sum_{m \in M_i} C_m^{inv}(y_m)$$

subject to

$$\begin{aligned}
&P_j = a_j - b_j \cdot (X_{i,j} + X_{-i,j}), \ \forall j \\
&cap_m^0 + y_m - \sum_j x_{m,j} \geq 0, \ \forall m \in M_i \ (\lambda_m) \\
&y_m^{max} - y_m \geq 0, \ \forall m \in M_i \ (\theta_m) \\
&x_{m,j} \geq 0, \ \forall m \in M_i, j \\
&y_m \geq 0, \ \forall m \in M_i
\end{aligned}$$

while taking the supplies $X_{-i,j}$ of the other producers $(-i)$ as given. Here and in the following, we use the abbreviation $X_{I_1,j} = \sum_{i \in I_1} \sum_{m \in M_i} x_{m,j}$ for some $I_1 \subset I$.

Hence, in the perfect competition model, each producer *simultaneously* makes his ("long-term") investment and ("short-term") production decisions in order to maximize profits. In doing so, each producer takes capacity restrictions into account. However, players do not take into account their influence on price.

Any solution to the above optimization problem has to satisfy the short-term Karush-Kuhn-Tucker (KKT) conditions

$$
\begin{aligned}
&0 \le \frac{\partial C_m^{var}(\mathbf{x}_m)}{\partial x_{m,j}} - [a_j - b_j \cdot (X_{i,j} + X_{-i,j})] + \lambda_m \perp x_{m,j} \ge 0,\ \forall i, m \in M_i, j \\
&0 \le cap_m^0 + y_m - \sum_j x_{m,j} \perp \lambda_m \ge 0,\ \forall i, m \in M_i
\end{aligned}
$$

as well as the long-term KKT conditions

$$
\begin{aligned}
&0 \le k_m - \lambda_m + \theta_m \perp y_m \ge 0,\ \forall i, m \in M_i \\
&0 \le y_m^{max} - y_m \perp \theta_m \ge 0,\ \forall i, m \in M_i.
\end{aligned}
$$

In equilibrium, all KKT conditions have to hold simultaneously. Uniqueness of the solution is guaranteed due to the quasi-concave objective function and the convexity of the restrictions. The derived KKT conditions are thus necessary and sufficient for obtaining the solution.

4.2.3 Model 2: The Open-Loop Cournot Model with Competitive Fringe

In the open-loop Cournot model with competitive fringe (in the following simply termed 'open-loop model'), each producer $i \in I$ solves an optimization problem identical to the one for the perfect competition model described above. However, each producer may take additionally into account his influence on price which is represented by the conjectural variation parameter ψ_i, where $\frac{\partial P_j}{\partial x_{m,j}} = \psi_i \cdot b_j$ for all $m \in M_i$. Cournot behavior with a competitive fringe can then be represented as $\psi_i = 1$ for the Cournot players and $\psi_i = 0$ for the competitive fringe.[14]

Any solution to the open-loop Cournot model with competitive fringe then satisfies the short-term Karush-Kuhn-Tucker (KKT) conditions

$$
\begin{aligned}
&0 \le \frac{\partial C_m^{var}(\mathbf{x}_m)}{\partial x_{m,j}} - [a_j - b_j \cdot (X_{i,j} + X_{-i,j})] + \psi_i \cdot b_j \cdot X_{i,j} + \lambda_m \perp x_{m,j} \ge 0, \\
&\forall i, m \in M_i, j \\
&0 \le cap_m^0 + y_m - \sum_j x_{m,j} \perp \lambda_m \ge 0,\ \forall i, m \in M_i
\end{aligned}
$$

[14] The perfect competition model also follows from this specification by setting $\psi_i = 0$ for all i.

as well as the long-term KKT conditions

$$0 \leq k_m - \lambda_m + \theta_m \perp y_m \geq 0, \ \forall i, m \in M_i$$
$$0 \leq y_m^{max} - y_m \perp \theta_m \geq 0, \ \forall i, m \in M_i.$$

In equilibrium, the KKT conditions of both the Cournot players and the competitive fringe have to hold simultaneously. As in the perfect competition case, uniqueness of the solution is guaranteed due to the quasi-concave objective function and the convexity of the restrictions. The derived KKT conditions are therefore again necessary and sufficient for obtaining the solution.

4.2.4 Model 3: The Closed-Loop Model

In the closed-loop model, producers play a two-stage game: In the first stage, oligopolistic producers l ($l \in L \subset I$) decide on their investment levels. In the second stage, they choose, based on *observed* investment decisions of the other oligopolistic producers, their production and supply levels. In addition, in the second stage, a further player, the competitive fringe (F), makes his supply decisions. The competitive fringe is not allowed to invest in either stage.[15] As opposed to the oligopolistic producers, the competitive fringe is a price taker.

4.2.4.1 The Second Stage Problem

For a given investment vector (y_l, y_{-l}) of the oligopolistic producers, let the second stage problem of producer i be given by

$$\max_{x_{m,j}:m \in M_i} \sum_{m \in M_i} \big(\sum_{j \in J} P_j \cdot x_{m,j} - C_m^{var}(\mathbf{x}_m) \big)$$

subject to

$$P_j = a_j - b_j \cdot (X_{i,j} + X_{-i,j}), \ \forall j$$
$$cap_m^0 + y_m - \sum_j x_{m,j} \geq 0, \ \forall m \in M_i \ (\lambda_m)$$
$$x_{m,j} \geq 0, \ \forall m \in M_i, j.$$

[15] In our application to the metallurgical coal market, this restriction also holds true for the player in the perfect competition model corresponding to the competitive fringe in the closed-loop model as well as for the competitive fringe in the Cournot open-loop model. For better readability, the model descriptions in the preceding two subsections are slightly more general, i.e., allowing potentially all players to invest.

As in the open-loop model, producer i decides on his supplies while taking the supplies of the other producers $(-i)$ as given. A producer's influence on price is again assumed to be represented by a conjectural variation parameter ψ_i, which is equal to one for the oligopolistic producers and zero for the competitive fringe. Note that the competitive fringe may not invest and therefore $y_m = 0$ for the fringe. The corresponding KKT conditions to this problem are then given by

$$
\begin{aligned}
&0 \leq \frac{\partial C_m^{var}(\mathbf{x}_m)}{\partial x_{m,j}} - [a_j - b_j \cdot (X_{i,j} + X_{-i,j})] + \psi_i \cdot b_j \cdot X_{i,j} + \lambda_m \perp x_{m,j} \geq 0, \\
&\forall m \in M_i, j \\
&0 \leq cap_m^0 + y_m - \sum_j x_{m,j} \perp \lambda_m \geq 0, \ \forall m \in M_i.
\end{aligned}
$$

In the second stage equilibrium, the KKT conditions of all producers have to hold simultaneously. In the following, let $\tilde{x}_{m,j}(y_l, y_{-l})$ denote the second stage production equilibrium for a given investment vector (y_l, y_{-l}).

4.2.4.2 The First Stage Problem

The first stage problem for oligopolistic producer $l \in L$ is given by

$$
\max_{y_m : m \in M_l} \sum_{m \in M_l} \big(\sum_{j \in J} \tilde{P}_j \cdot \tilde{x}_{m,j}(y_l, y_{-l}) - C_m^{var}(\tilde{\mathbf{x}}_m(y_l, y_{-l})\big) - \sum_{m \in M_l} C_m^{inv}(y_m)
$$

subject to

$$
\begin{aligned}
&\tilde{P}_j = a_j - b_j \cdot (\tilde{X}_{l,j}(y_l, y_{-l}) + \tilde{X}_{-l,j}(y_l, y_{-l}) + \tilde{X}_{F,j}(y_l, y_{-l})), \ \forall j \\
&y_m^{max} - y_m \geq 0, \ \forall m \in M_l \\
&y_m \geq 0, \ \forall m \in M_l,
\end{aligned}
$$

i.e., producer l chooses his investment levels in order to maximize profits for a given investment strategy of the other oligopolistic producers (y_{-l}) under consideration of the resulting second stage equilibrium outcome.

Combining the second stage and the first stage problem, we obtain the following MPEC for producer l, hereafter referred to as MPEC$_l$:

$$
\max_{\Omega_l} \sum_{m \in M_l} \big(\sum_{j \in J} (a_j - b_j \cdot (X_{l,j} + X_{-l,j} + X_{F,j})) \cdot x_{m,j} - C_m^{var}(\mathbf{x}_m)\big) - \sum_{m \in M_l} C_m^{inv}(y_m)
$$

subject to

$$y_m^{max} - y_m \geq 0, \ \forall m \in M_l$$

$$y_m \geq 0, \ \forall m \in M_l$$

$$0 \leq \frac{\partial C_m^{var}(\mathbf{x}_m)}{\partial x_{m,j}} - [a_j - b_j \cdot (X_{i,j} + X_{-i,j})] + \psi_i \cdot b_j \cdot X_{i,j} + \lambda_m \perp x_{m,j} \geq 0,$$
$$\forall i, m \in M_i, j$$

$$0 \leq cap_m^0 + y_m - \sum_j x_{m,j} \perp \lambda_m \geq 0, \ \forall i, m \in M_i$$

given the investment vector (y_{-l}) of the other oligopolistic producers. Here, Ω_l is given by
$\Omega_l = \{(y_m)_{m \in M_l}; \quad (x_{m,j}, \lambda_m)_{m \in M, j \in J}\}$.[16]

An investment strategy $(\tilde{y}_l, \tilde{y}_{-l})$ is a closed-loop equilibrium if for all $l \in L$, $\tilde{y}_l$ solves l's MPEC problem MPEC$_l$ given $\tilde{y}_{-l}$. The problem of finding a closed-loop equilibrium is hence of EPEC type (Gabriel et al., 2012), and therefore existence and uniqueness of equilibria typically is non-trivial and parameter dependent.

4.2.5 Discussion of the Models and Equilibrium Concepts

Closed-loop strategies allow players to condition their actions on actions taken in previous time periods; in open-loop strategies, this is not possible. Thus, equilibria in the closed-loop model are by definition subgame perfect, whereas open-loop equilibria are typically merely dynamically (time) consistent. The latter is a weaker equilibrium concept than subgame perfection. It requires only that no player has an incentive at any time to deviate from the strategy he announced at the beginning of the game, "given that no player has deviated in the past and no agent expects a future deviation" (Karp and Newbery, 1992). Therefore, with subgame perfect equilibria requiring actions to be optimal in every subgame of the game, i.e., requiring that no player has an incentive to deviate from his strategy regardless of any deviation in the past, an equilibrium of the open-loop model may fail to be an equilibrium in the closed-loop game.[17]

Fudenberg and Tirole (1991) and the literature cited therein generally address the issue of diverging results of open-loop models in comparison to closed-loop models and provide intuition for the divergence: In the closed-loop model, in contrast to the open-loop model, a player's influence via its own actions in the first stage on the other players'

[16] Note that the first stage decision variable is separated from the second stage decision variables by a semicolon. The latter are indirectly determined by the choice of the first stage decision variable.

[17] See Selten (1965) for the first formalization of the concept of subgame perfect equilibria and, e.g., Karp and Newbery (1989) for a general account on dynamic consistency.

actions in the second stage is taken into account. Applying this intuition to the special case of the capacity expansion problem, Murphy and Smeers (2005) show that in the closed-loop equilibrium, marginal investment costs may be higher than the sum of the short-term marginal value implied by the KKT conditions. In particular, they note that "the difference between the two characterizes the value for the player of being able to manipulate the short-term market by its first stage investments." This may lead to higher investments and supplies and hence lower prices in the closed-loop model compared to the open-loop model.

The existing literature on the subject, in particular the above mentioned Murphy and Smeers (2005) as well as Wogrin et al. (2013b), provides general properties of closed-loop and open-loop models and conditions for diverging and non-diverging results between the two models, assuming simplified settings (e.g., ignoring existing capacities). We conjecture that in a spatial application with non-generic data and existing capacities available to the players, equilibria are likely to deviate between the two modeling approaches, which is confirmed by our application to the metallurgical coal market (see Sections 4.4 and 4.5). Analytical analysis is no longer available in this setting due to increased complexity and thus makes a numerical analysis necessary. The numerical approach is also suitable to address an issue which to our knowledge has not yet been comprehensively touched upon in previous literature: a quantification of the magnitude of the divergence between closed-loop and open-loop model results.

4.3 Implementation

4.3.1 Model 1: The Open-Loop Model

Both open-loop models introduced in Section 4.2, i.e., the open-loop perfect competition model and the open-loop Cournot competition model with competitive fringe, are implemented as mixed complementarity problems (MCP).

4.3.2 Model 2: The Closed-Loop Model

We solve the closed-loop model using diagonalization (see for instance Gabriel et al., 2012):

1. Set starting values for the investment decisions y_l^0 of all oligopolistic producers $l \in L$, a convergence criterion ϵ, a maximum number of iterations N and a learning rate R

2. $n = 1$
3. Set $y_l^n = y_l^{n-1}$
4. Do for all $l \in L$
   (a) Fix the investment decisions y_{-l}^n of $-l$
   (b) Solve player l's MPEC problem MPEC$_l$ to obtain an optimal investment level y_l
   (c) Set y_l^n equal to $R \cdot y_l + (1 - R) \cdot y_l^n$
5. If $|y_l^n - y_l^{n-1}| < \epsilon$ for all producers $l \in L$: quit
6. If $n = N$: quit
7. $n = n + 1$ and go back to step 3

Diagonalization thus reduces the closed-loop problem to a series of MPEC problems. Concerning the solution of the MPECs, we implement two procedures: grid search along the investment decision y_l and a reformulation of the MPEC as a Mixed Integer Linear Program (MILP).

Both approaches differ with respect to the simplification of the decision variables: With grid search we discretize the investment decision which is reasonable for many investment choices in real life. Thus, solving the MPEC problem reduces to solving a series of MCP problems with the choice of production volumes remaining continuous. On the contrary, in the MILP approach we discretize the production decisions but retain a continuous choice of investments in new capacity. The discretization may result in missing the global optimal solution.[18] As both approaches result in very similar outcomes (see Section 4.6) we are confident that our obtained results are valid.

Implementing both the grid search and MILP reformulation allows for the comparison of the computer run-times of the two models, with grid search typically being faster for reasonable grid sizes (see Section 4.6 for details on this issue).

4.3.2.1 Grid Search

When applying grid search along the investment decision y_l, MPEC$_l$ simplifies to a sequence of complementarity problems. In our implementation, the grid width in the grid search is the same for all producers; the number of steps for a producer is thus dependent on his capacity expansion limit.

[18] A third way of approaching the non-linearities in the model might be using the strong duality theorem to linearize the original MPEC as described in Ruiz and Conejo (2009).

4.3.2.2 MILP Reformulation

In addition to grid search, we implement a MILP reformulation of the MPEC. Non-linearities arise in the MPEC due to the complementarity constraints and the non-linear term in the objective function. The former are replaced by their corresponding disjunctive constraints (see Fortuny-Amat and McCarl, 1981), e.g., we replace

$$0 \leq cap_m^0 + y_m - \sum_j x_{m,j} \perp \lambda_m \geq 0$$

by

$$\begin{aligned} &M^\lambda b_m^\lambda \geq \lambda_m \\ &M^\lambda (1 - b_m^\lambda) \geq cap_m^0 + y_m - \sum_j x_{m,j} \end{aligned}$$

for some suitably large constant M^λ and binary variables b_m^λ.

For the discretization of the non-linear term in the objective function, we proceed following Pereira et al. (2005) using a binary expansion of the supply variable. The binary expansion of $x_{m,j}$ is given by

$$x_{m,j} = \underline{x} + \Delta_x \sum_k 2^k b_{k,m,j}^x,$$

where $\underline{x}$ is the lower bound, Δ_x the stepsize, k the number of discretization intervals and $b_{k,m,j}^x$ binary variables. Substituting $P_j \cdot \underline{x} + \Delta_x \sum_k 2^k z_{k,m,j}^x$ for $P_j \cdot x_{m,j}$, we have to impose the additional constraints

$$\begin{aligned} &0 \leq z_{k,m,j}^x \leq M^x b_{k,m,j}^x \\ &0 \leq P_j - z_{k,m,j}^x \leq M^x (1 - b_{k,m,j}^x) \end{aligned}$$

for some suitably large constant M^x.

4.4 Data Set

The models are parametrized with data for the international metallurgical coal market (see Table 4.1 and Appendix C.1). Yet, as the structure of the international metallurgical coal trade is (from a modeling perspective) similar to that of other commodities, the model could easily be calibrated with data for other markets.

Metallurgical coal is used in steel-making to produce the coke needed for steel production in blast furnaces and as a source of energy in the process of steel-making. Metallurgical coal is distinct from thermal coal, which is typically used to generate electricity or heat. Currently around 70% of the global steel production crucially relies on metallurgical coal as an input.[19]

International trade of metallurgical coal amounted to 250 million tonnes (Mt) in 2012.[20] International trade is predominantly seaborne, using dry bulk vessels. Up until 2010, metallurgical coal was almost exclusively traded through long-term contracts. Since then, the market has begun to move away from this system towards more spot market-based trading. While the share of spot market activity has increased rapidly, a substantial amount of metallurgical coal is still traded through long-term contracts.

Key players in this market are large mining companies such as BHP-Billiton, Anglo-American, Glencore and Rio Tinto. These companies produce mainly in Australia and, together with Peabody Energy's Australian operations, control more than 50% of the global export capacity. In addition, adding to this the market share of the Canadian Teck consortium and the two key metallurgical coal exporters from the United States, Walter Energy and Xcoal, results in almost three quarters of the global export capacity, marketed by an oligopoly of eight companies. For the sake of simplicity and computational tractability, we aggregate these players' existing mines into one mining operation per player. Smaller exporters from Australia, the United States, Russia, New Zealand, Indonesia and South Africa are aggregated into three players: one Cournot player from Australia (AUS6), one Cournot player from the United States (USA1) and one competitive fringe player that comprises all other regions (Fringe). This results in eleven asymmetric players who differ with respect to their existing production capacity and the associated production and transport costs (see Table 4.2).[21]

We assume that the three players representing the smaller exporters, i.e., USA1, AUS6 and Fringe, cannot invest in additional capacity. Hence, only the largest eight companies can endogenously expand their supply capacity. The investment decision, made in period one, is based on the players' capacities and costs in 2011. We consider one investment cycle with capacities becoming available after six years (i.e., in 2017) serving one demand period. Investment costs per tonne of annual production capacity (tpa) are broken down into equal annual payments based on an annuity calculation using an interest rate of 10% and a depreciation time of 10 years. The profitability of investments is evaluated based on the comparison of annuity and profits in the considered production period. We therefore assume that returns are constant over the years of production. Note that

[19]See WCA (2011).
[20]See IEA (2013a).
[21]Data on capacities and costs are taken from Trüby (2013).

Table 4.2: Existing Capacity, Variable and Investment Costs

Players	Existing Capacity [Mtpa]	Variable Costs [US$/t]	Investment Costs [US$/tpa]	Max. Investment [Mtpa]
USA1	38	122.0	-	-
USA2	9	122.1	98.2	50
USA3	11	141.0	98.0	50
AUS1	54	118.3	218.1	50
AUS2	11	118.4	218.0	50
AUS3	17	118.5	217.9	50
AUS4	10	118.6	217.8	50
AUS5	12	118.0	218.2	50
AUS6	18	118.1	-	-
CAN	26	105.0	161.0	20
Fringe	26	78.0	-	-

production cost of new mines correspond to the production cost of the respective player's existing mine.

The two largest importers of metallurgical coal are Europe and Japan, followed by India, China and Korea. These key importers account for more than 80% of the trade. We aggregate these and the remaining smaller countries into two demand regions: Europe-Atlantic and Asia-Pacific.[22] The former also includes the Mediterranean's neighboring countries and importers from the Atlantic shores of the Americas. The latter includes importers with coastlines on the Pacific or the Indian Ocean. Exporters from the United States have a transport cost advantage in the Europe-Atlantic region, while Canadian and Australian exporters are located closer to the consumers in the Asia-Pacific region (see Table C.1 in Appendix C.1). We assume the inverse import demand function for metallurgical coal to be linear. The function can be specified using a reference price and a corresponding reference quantity in combination with a point-elasticity *eta*.

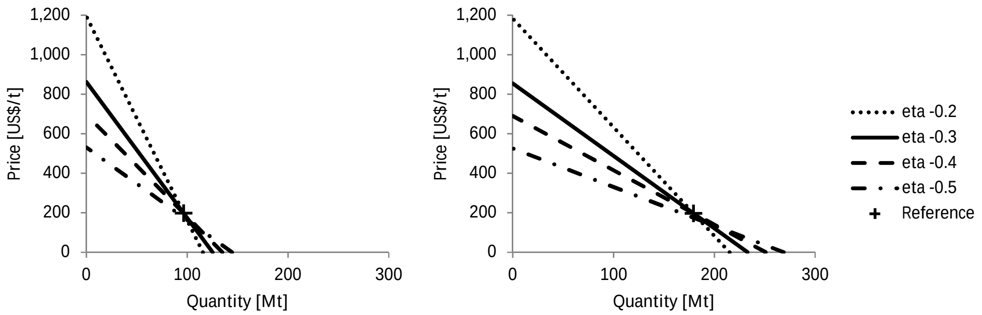


Figure 4.1: Demand functions for Europe-Atlantic (left) and Asia-Pacific regions (right) with varying elasticity

[22]Our approach covers 100% of the global seaborne metallurgical coal imports and exports (based on data from 2011).

4.5 Results

In practice, investors in production capacity face demand evolution as a key uncertainty. Accounting for this uncertainty, we run sensitivities in which we vary the point-elasticity parameter *eta* across the range -0.2 to -0.5 (see Figure 4.1).[23] This bandwidth is generally considered reasonable in the metallurgical coal market (see Trüby, 2013, and the literature cited therein). Furthermore, we vary the reference demand quantity (see Table C.2 in Appendix C.1) from 60% to 140% to account for different demand evolution trajectories. The presentation of the results is structured around the variation of these demand parameters followed by a general discussion of the findings.

4.5.1 Variation of Demand Elasticity

Decreasing the point elasticity parameter *eta* results in a flatter gradient of the linear demand function (see Figure 4.1). A decreasing *eta* (i.e., a more negative *eta*) expresses an increasing price responsiveness of consumers which, *ceteris paribus*, limits the extent to which the oligopolists can exploit their market power. Consequently, with decreasing *eta*, average prices achieved in the imperfect competition cases (open-loop and closed-loop) are decreasing while total production is increasing (Figure 4.2). Note that in the perfect competition case, the aggregate supply and the aggregate demand curves intersect below the reference point resulting in an increase in production with decreasing *eta* and, correspondingly, with increasing marginal costs, an increase in production results in an increase in price. In the two Cournot models with imperfect competition the oligopolistic mark-up on marginal costs leads to market prices exceeding the reference price.

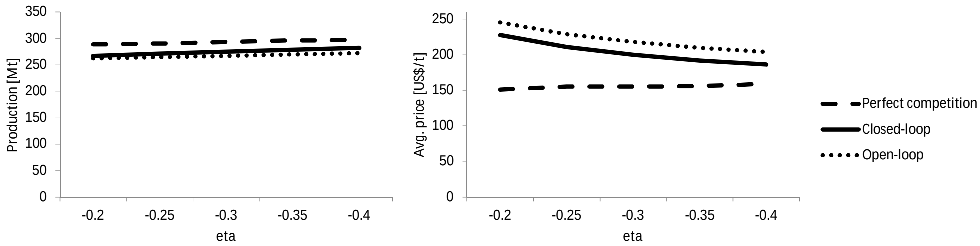


Figure 4.2: Total production (left) and average market price (right) for varying demand elasticity

[23]For *eta* smaller than -0.4, closed-loop model runs did not converge. Therefore, the results presented in this section only comprise the range -0.2 to -0.4. For a discussion on computational issues, see Section 4.6.

A variation of *eta* impacts the investment trends differently in the three cases (Figure 4.3). However, the capacity expansion investments need to be interpreted in concert with the corresponding utilization of the existing capacity. Intuitively, one would expect investment into additional capacity to be highest in the perfect competition case. Yet, in our setup, the investment level in the perfectly competitive case falls between the two cases with imperfect competition. This effect stems from the significant amount of existing capacities which – with the exception of some very high-cost capacities – are utilized before additional production capacity is built. Murphy and Smeers (2005) show that in their model which does not account for existing capacities, investment levels are indeed highest under perfect competition.

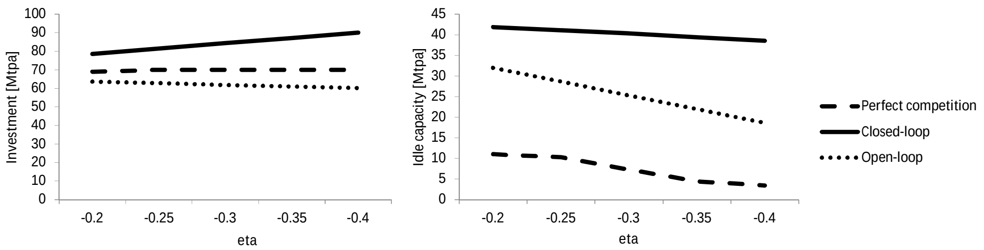


Figure 4.3: Capacity investments (left) and idle capacity (right) for varying demand elasticity

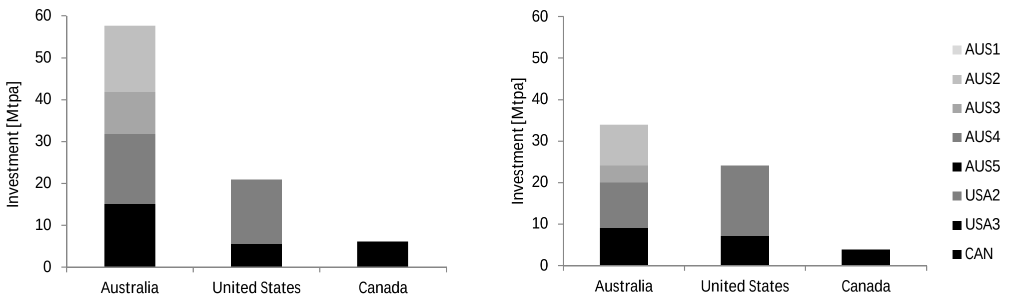


Figure 4.4: Capacity investments for the closed-loop (left) and open-loop model (right) ($eta = -0.3$)

Of particular interest is the ranking of the closed-loop and open-loop case in terms of capacity expansion and capacity withholding. Note that withholding (or idle capacity), here and in the following, concerns only exiting capacities. Each player exhausts existing capacities before investing in additional capacities. Newly built capacities are always fully utilized in equilibrium as otherwise players could increase their profit by reducing investments. Investments in the open-loop case are strictly lower than in the closed-loop case independent of the elasticity while less capacity is withheld in the open-loop case. However, the investment behavior of individual players may differ from the aggregate industry behavior; as can be seen in Figure 4.4 two players from the United States invest more in the open-loop model than in the closed-loop model contrary to what the rest of the industry does.

To get an intuition for the investment behavior in the open-loop case, suppose that there are two players, an incumbent with infinite existing capacity and an entrant without any capacity.[24] Both players face the same production cost while investment costs are non-zero. Under these assumptions, the incumbent has no incentive to invest in additional capacity as his capacity endowment is sufficient to produce the Nash-Cournot-output. Contrarily, the entrant builds as much capacity as is required to produce the amount needed in equilibrium (marginal revenue equals the sum of marginal production and investment cost). Similarly, in our application to the metallurgical coal market with heterogeneous cost structures, investment primarily comes from the players with relatively small existing capacity, while larger players withhold capacity in period two when the market clears.

The investment level is higher in the closed-loop case compared to the open-loop case as the capacity expansion in the first period can be used strategically to influence the supply decisions of the other players in the second period. Despite the bi-level structure of this game, no player has a first mover advantage as investment decisions are taken simultaneously by all players. The production decision is based on realized investments and investment costs are considered as being sunk. This way, the choice of capacity investments can only influence other players' production decisions.

To get an intuition for the investment behavior in the closed-loop case, again suppose for a moment that there are two players, an incumbent with infinite existing capacity and an entrant without any capacity. Both players face the same production cost while investment costs are non-zero (if investment costs were zero the result would converge to the open-loop case). As there is no long-term contract, the entrant's investment cost is sunk in period two and his production decision is solely based on the production costs. Therefore, the entrant's desired production, given sufficient capacity, is higher compared to a situation where investment costs feature in the first-order-condition (as in the open-loop case). At the same time, the incumbent's reaction would be to reduce his production. Anticipating this, the entrant has an incentive to build a higher capacity level than in the open-loop case. This way, the entrant can influence the incumbent's output decision in period two by his choice of capacity in period one. An analytical solution of this game becomes non-trivial when more than one player makes subsequent investment and supply decisions as these decisions mutually influence each other. Yet, this little example is useful to provide a better understanding of why the closed-loop

[24]This and the following intuition for the deviations in the closed-loop case are presented in an analytical example in more detail in Appendix C.2.

case features higher investment levels but also higher withholding of existing capacities than the open-loop case.

In both models of imperfect competition, capacity is exclusively withheld by the two largest players in the market, one producing in Australia and the other one in the United States. Capacity expansion and withholding are following opposing trends in our models of imperfect competition, i.e., the open-loop model exhibits a lower level of investment but also a lower level of unused capacity while the higher investment levels in the closed-loop model come with a higher level of idle capacity. Thus, it is a-priori unclear how the two models would rank in terms of total supply and market prices. A numerical solution of our models yields that supply is higher in the closed-loop case than in the open-loop case. Consequently, market prices are lower in the closed-loop case. This result is in line with the findings of Murphy and Smeers (2005).

Industry profits, consumer rent and social welfare are depicted in Figure 4.5. Industry profits decrease with decreasing *eta* and so does consumer rent (a higher price-responsiveness of consumers limits market power exploitation but also potential consumer rent). The existence of profits in the perfect competition model is due to capacity restrictions of existing mines and limited expansion potential for new mines. Social welfare is similar in all three models: in a perfectly competitive market welfare is slightly higher than in the Cournot models. Welfare is lowest in the open-loop case (Figure 4.6). Thus, the different underlying assumptions concerning the prevailing market structure in the international metallurgical coal trade (long-term contracts versus spot market) primarily influences the surplus distribution rather than its sum: in the open-loop case in which the product is traded through long-term contracts, companies can earn higher profits, while consumer surplus is higher in markets with spot market-based trade.

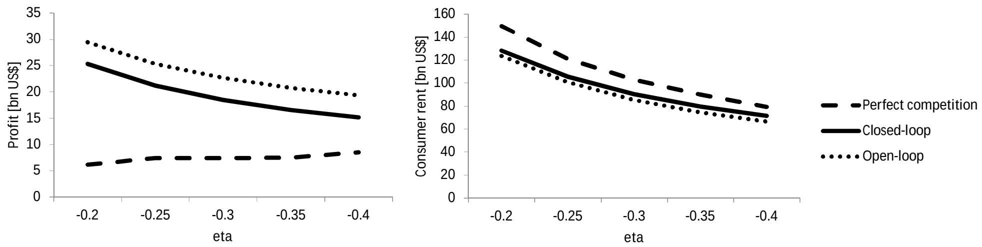


Figure 4.5: Accumulated profits (left) and consumer rent (right) with varying demand elasticity

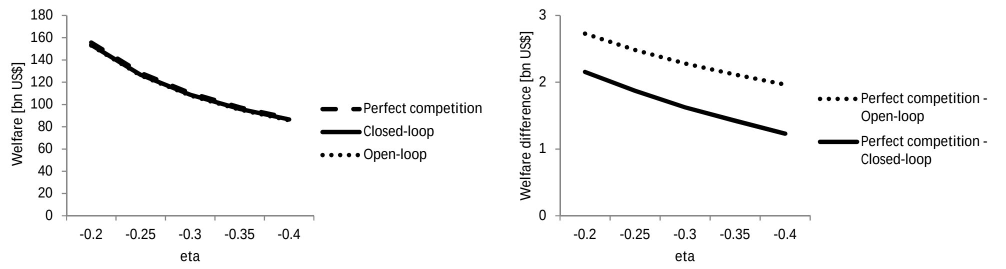


Figure 4.6: Overall welfare (left) and welfare differences (right)

4.5.2 Variation of Reference Demand

For the variation of reference demand, the point elasticity *eta* has been fixed to a value of -0.3; thus the case of 100% reference demand corresponds to the depicted results of the previous subsection with the same demand elasticity. Variations of the reference demand results in a shift of the demand curve to the right for values larger than 100% and a shift to the left for values lower than 100%.

As in the previous subsection, supply is highest under perfect competition and lowest in the open-loop case for any demand variation (Figure 4.7). Accordingly, prices are highest in the open-loop case followed by the closed-loop and the perfect competition cases. As one would expect, supply and average prices increase with increasing demand.

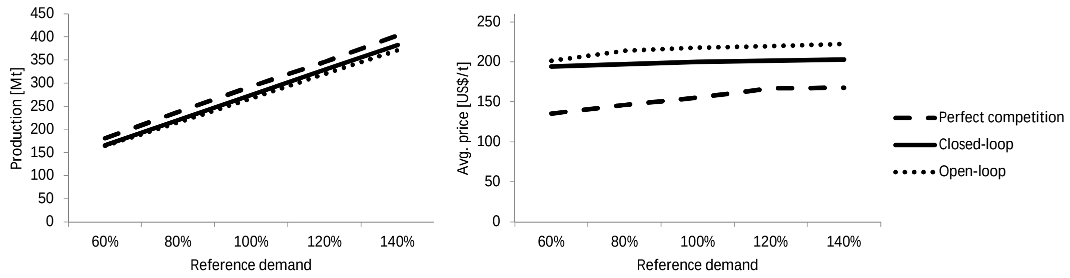


Figure 4.7: Total production (left) and average market price (right) for varying reference demand

For low reference demand levels, the existing capacities of small players are almost sufficiently high to produce the quantities needed for their best-supply response in period two. Therefore, the results in the open-loop and closed-loop cases almost coincide at 60% reference demand as investment activity is low. Investments in additional production capacity are increasing monotonously with growing reference demand (Figure 4.8). As with the variation of the demand elasticity, investments are consistently lower in the open-loop case than in the closed-loop case. For low demand levels, investments in the competitive model are below those in the models with imperfect competition as existing capacities are sufficient to serve demand rendering investments unprofitable. In the

Cournot models, investment into additional production capacity is still profitable for small players as they can count on players with large existing capacities to withhold some output.

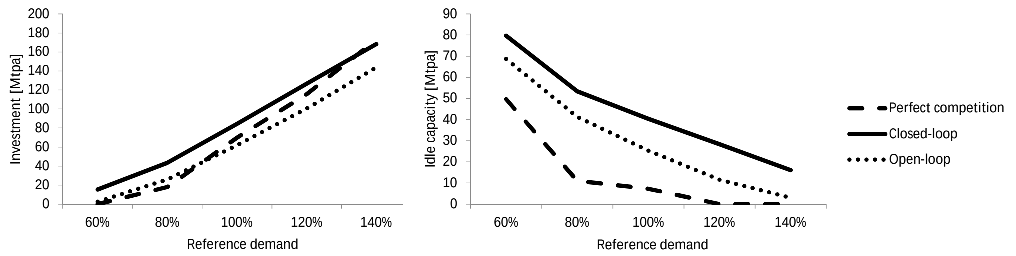


Figure 4.8: Capacity investments (left) and idle capacity (right) for varying reference demand

For high demand levels, investments under perfectly competitive conduct exceed those even in the closed-loop model. The order of idle capacity is similar to the case of varying demand elasticity: idle capacity is highest in the closed-loop model followed by the open-loop case (both due to strategic considerations) and the perfect competition model (due to market prices below the marginal costs of costlier capacities).

With increasing demand, profits as well as consumer rents increase (Figure 4.9). Again, results for the open-loop and closed-loop cases almost coincide if reference demand is very low as investments play a minor role. In the case of high reference demand, profits in the open-loop model exceed those in the closed-loop model. Results for consumer rents are vice versa. Total welfare turns out to be quite similar for all three models with the highest welfare occurring in the perfectly competitive model followed by the closed-loop and open-loop models (Figure 4.10).

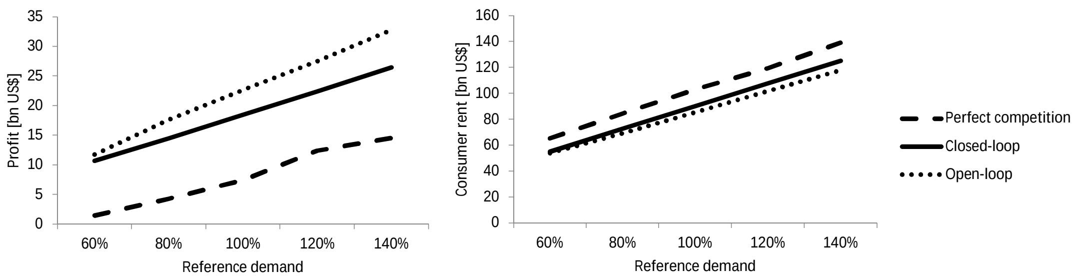


Figure 4.9: Accumulated profits (left) and consumer rent (right) with varying reference demand

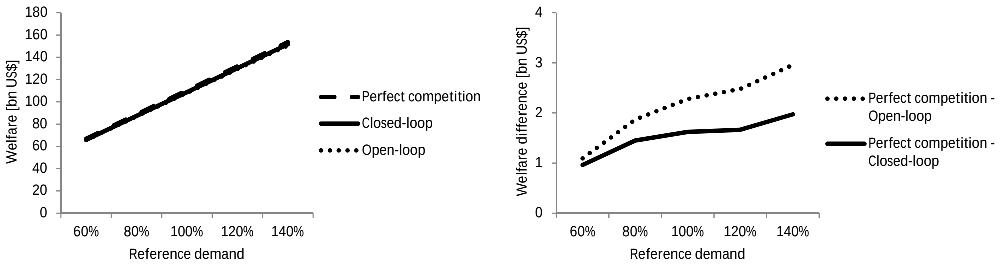


Figure 4.10: Overall welfare (left) and welfare difference (right, open-loop minus closed-loop)

4.5.3 Summary

Asymmetric existing capacities are an important driver of our results. While welfare is highest in the perfect competition case, investment levels in this case fall between the two Cournot models as existing capacities are sufficient to absorb additional demand. Profits are highest in the open-loop case followed by the closed-loop and perfect competition models. Moving away from long-term contracts towards a spot market-based trade reduces profits of all players, however, companies with large existing capacities are affected to a larger degree: the two large firms (one from Australia and one from the United States) who are responsible for the withholding of capacity in the Cournot models together receive 23% of the industry profits in the open-loop case but see their share of profits diminished to 17% in the closed-loop case.

In our modeling setup the competitive fringe has no strategic relevance. Fringe players neither invest nor withhold, i.e., they always produce to capacity. In essence, the fringe determines the residual demand that the oligopolists optimize against but it does not introduce any sort of first-mover vs. follower relationship.

The magnitude of result deviations between the different models, and thus the implications for market participants are quite significant. The models of imperfect competition differ, for instance, in capacity expansions between 19% and up to 33% (low and high demand elasticity, respectively).

Even though social welfare differs only slightly between the open-loop and closed-loop models in our calculations for the metallurgical coal market, the difference may be higher for other markets with different model parameters. In addition, the surplus distribution between consumer rent and profits differs significantly and has policy implications since – in natural resource markets – production and consumption take place in different countries.

4.6 Computational Issues

Equilibria in a closed-loop model, if any exist, do not necessarily have to be unique. Therefore, we perform a robustness check for our closed-loop results by using different starting values for capacity investments. Starting values are randomly drawn from a reasonable range of possible investments, with the maximum investment of each player as given in Table 4.2. Limiting the range of possible investments drastically reduces computer run-times and increases the probability of finding equilibria. In addition, calculations are made with starting values set to zero and to the open-loop results. The algorithm terminates if overall adjustments of investments δ are less than $\epsilon = 0.1$ Mtpa compared to the previous iteration. We use a learning rate parameter R for the adoption rate of new investments in order to avoid cycling behavior. The learning rate parameter is randomly set between 0.6 and 1.0 (see Gabriel et al., 2012). Calculations have been done on a 16 core server with 96 GB RAM and 2,67 GHz using CPLEX 12.2.

Table 4.3 shows calculation statistics when using the MILP version of our model (see Subsection 4.3.2.2). We perform six runs per parameter setting using random starting values. Most runs converged to an equilibrium before the maximum number of iterations was reached. With increasing demand elasticity, the algorithm had difficulties to converge. In the case of $eta = -0.4$, only every third run converged to an equilibrium; for $eta < -0.4$, no equilibrium could be found at all. Using either zero investments or open-loop results as starting values, a closed-loop equilibrium was found, except for $eta < -0.4$.

Table 4.3: Computation time and convergence to equilibrium - MILP version (random, zero, open-loop starting values)

Scenario	Convergence (max. 10 iterations)	Iterations until convergence (only converged runs, max. 10)	Calculation time (only converged runs) [h]
reference case (eta -0.3, dem 1.0)	6/6, yes, yes	6-7 (avg. 6.8), 7, 6	10.7-13.7 (avg. 12.4), 7.1, 5.2
eta -0.2	6/6, yes, yes	7-8 (avg. 7.3), 6, 6	9.2-14.1 (avg. 11.0), 5.7, 4.1
eta -0.25	6/6, yes, yes	7-10 (avg. 8.2), 7, 6	11.4-14.9 (avg. 12.8), 6.9, 5.5
eta -0.35	6/6, yes, yes	6-8 (avg. 7.2), 6, 6	11.3-15.8 (avg. 12.7), 5.1, 5.6
eta -0.4	2/6, yes, yes	7-8 (avg. 7.5), 9, 7	12.2-12.7 (avg. 12.4), 5.6, 7.8
eta -0.45	0/6, no, no	-, -, -	-, -, -.
eta -0.5	0/6, no, no	-, -, -	-, -, -
dem 0.6	5/6, yes, yes	7-9 (avg. 7.4), 7, 7	1.9-3.5 (avg. 2.2), 0.1, 0.2
dem 0.8	6/6, yes, yes	7-8 (avg. 7.5), 6, 5	3.6-8.8 (avg. 7.1), 2.0, 2.3
dem 1.2	6/6, yes, yes	6-9 (avg. 7.8), 7, 6	9.8-13.9 (avg. 11.9), 8.3, 6.0
dem 1.4	6/6, yes, yes	6-10 (avg. 8.3), 7, 6	7.7-11.2 (avg. 8.7), 9.7, 5.7

Figure 4.11 illustrates the iterative solution process for a single model run for $eta = -0.5$ using random starting values. The model run did not converge to an equilibrium.[25] After initial adjustments of investments in the first iterations, investments start to cycle in a rather small range. Total investments from iteration 5 to 10 vary between 89 Mtpa and 97 Mtpa. This range is typical for all runs regardless of the starting values. The maximum range for a single player's investment deviations is 3 Mtpa. Thus, even if no equilibrium is reached, analyzing the solution process may hint to possible market developments.

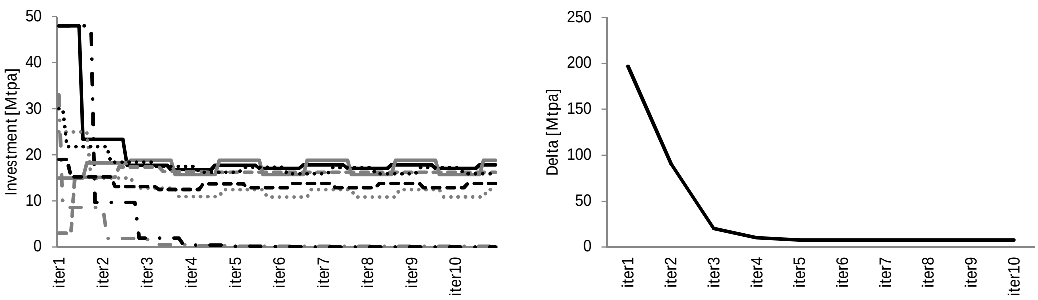


Figure 4.11: Course of investments of single players during solution process ($eta = -0.5$)

Using zero investments or open-loop equilibrium results as starting values led to a significant reduction of computer run-times compared to random starting values. This is probably due to the rather large range of random starting values and the (comparably) rather small equilibrium investments. Thus, starting from zero investments in most cases is closer to the equilibrium values than starting with random values. In summary, using reasonable starting values can support the solution process significantly.

If the algorithm converged, model results were identical for all runs with the same parameters concerning demand level and demand elasticity. Thus, even if the existence of multiple equilibria cannot be excluded, equilibria appear to be stable.

Calculations using the MILP version of our model usually took several hours to converge to an equilibrium. Applying the grid search approach (see Subsection 4.3.2.1) reduced computer run-times significantly. The conceptional difference between both approaches lies in the simplification of the decision variables: With grid search we discretize the investment decision. On the contrary, in the MILP approach we discretize the production decisions but retain a continuous choice of investments in new capacity.

The same calculations as in the MILP version have been done using grid search with investment steps of 0.1 Mtpa and the same convergence criterion as in the MILP version ($\epsilon = 0.1$ Mtpa). The model was implemented in GAMS using GUSS (see Bussieck et al., 2012).

[25]In our iterative approach, convergence depends on the choice of (an arbitrarily small) ϵ.

Table 4.4: Computation time and convergence to equilibrium - Grid Search (random, zero, open-loop starting values)

Scenario	Convergence (max. 10 iterations)	Iterations until convergence (only converged runs, max. 10)	Calculation time (only converged runs) [min]	Accumulated absolute difference between investments in MILP and grid version [%]
reference case (eta -0.3, dem 1.0)	6/6, yes, yes	6-7 (avg. 6.3), 7, 6	2.8-15.7 (avg. 9.3), 2.2, 2.4	0.7-0.9, 0.8, 0.8
eta -0.2	6/6, yes, yes	5-7 (avg. 6.3), 7, 5	3.5-16.7 (avg. 10.2), 2.3, 2.0	1.0, 1.0, 1.0
eta -0.25	6/6, yes, yes	6-7 (avg. 6.7), 7, 6	2.4-16.5 (avg. 9.4), 2.2, 2.4	0.8, 0.7, 0.8
eta -0.35	6/6, yes, yes	6-8 (avg. 7.0), 7, 6	2.8-17.5 (avg. 10.4), 2.2, 2.4	0.8-1.2, 1.2, 0.8
eta -0.4	6/6, yes, yes	6-7 (avg. 6.5), 7, 6	2.5-16.2 (avg. 9.3), 2.2, 2.4	1.2-1.5, 1.5, 1.5
eta -0.45	0/6, no, no	-, -, -	-, -, -.	-, -, -
eta -0.5	0/6, no, no	-, -, -	-, -, -	-, -, -
dem 0.6	6/6, yes, yes	6-8 (avg. 7.0), 5, 5	3.2-16.9 (avg. 9.7), 2.0, 2.0	2.5-3.7, 3.1, 3.3
dem 0.8	6/6, yes, yes	6-7 (avg. 6.7), 6, 6	2.8-16.2 (avg. 9.6), 2.6, 2.4	0.9, 1.0, 0.9
dem 1.2	6/6, yes, yes	5-7 (avg. 6.8), 7, 6	2.9-17.2 (avg. 10.1), 2.3, 2.5	0.3, 0.3, 0.3
dem 1.4	6/6, yes, yes	5-6 (avg. 6.3), 7, 6	2.9-16.1 (avg. 9.7), 2.3, 2.5	0.3-0.4, 0.4, 0.4

Applying grid search, the solution process took only several minutes to converge. Thus, reducing the optimization process from a series of computationally challenging MPECs to comparably easy-to-solve complementarity problems reduced overall computer runtime significantly. As for the MILP version, all model runs converged to the same equilibrium (for $eta \geq -0.4$) or did not converge at all (for $eta < -0.4$). Aggregated absolute deviations of investments between the MILP and the grid search version of our model vary between 0.3% and 3.7%. Thus, in our parameter setting, only minor differences in the results occurred.

4.7 Conclusions

We presented three investment models for oligopolistic spatial markets. Our approach accounts for different degrees of competition and as to whether the product is sold through long-term contracts or on spot markets. The models are particularly suited for the analysis of investments in markets for natural resources and minerals. We applied the models to the international metallurgical coal trade, which features characteristics similar to those of other commodity markets.

Results may differ substantially between the different models. The closed-loop model, which is computationally challenging, is particularly well suited for when the product is traded on a spot market and the investment expenditure is large compared to production costs. The open-loop model is appropriate for markets with perfect competition or imperfectly competitive markets on which the product is traded through long-term contracts. Moreover, the open-loop model approximates the closed-loop outcome when investment costs are minor.

Over the last several years, progress has been made in the metallurgical coal and iron ore markets to move away from long-term contracts and introduce spot markets in commodity trade. Similarly, efforts are being made to introduce spot market-based pricing between European natural gas importers and the Russian gas exporting giant Gazprom. Our results suggest that moving away from long-term contracts in oligopolistic markets is likely to stimulate additional investment and consequently reduce profits and increase consumer rents. The overall effect on welfare is negligible. However, in natural resource markets, export revenues and consumer rents from imports are typically accrued in different legislations. Hence, policy makers from exporting and importing countries are likely to have differing views on how commodity trade should be organized.

Further research is needed to improve methods for solving complex two-stage problems. In addition, further research could apply the models presented here to other oligopolistic mining industries such as the copper or iron ore trade. Given that static pricing models tend to give unsatisfactory results for the oil market, in which variable costs are low but capital expenditure is very high, the closed-loop approach may provide interesting insights into oligopolistic pricing when accounting for investments in capacity.

Chapter 5

The future of nuclear power in France: an analysis of the costs of phasing-out

Nuclear power is an important pillar in electricity generation in France. However, France's nuclear power plant fleet is ageing, and the possibility of reducing its share in power generation or even a complete phase-out has been increasingly discussed. Our research therefore focuses on three questions: First, what are the costs of phasing-out nuclear power in France under different scenarios? Second, who has to bear these costs, i.e., how much of the costs will be passed on to the rest of the European power system? And third, what effect does the uncertainty regarding future nuclear policy in France have on system costs? Applying a stochastic optimization model for the European electricity system, we show that additional system costs in France of a nuclear phase-out amount up to 76 billion €$_{2010}$. Additional costs are mostly borne by the French power system. Surprisingly, we find that the costs of uncertainty are rather limited. Based on our results, we conclude that a commitment regarding nuclear policy reform is only mildly beneficial in terms of system costs.

5.1 Introduction

Nuclear power is an important technology in the global electricity system, comprising a share of 13% of global power generation (IEA, 2012). Its contribution to electricity generation is currently substantially higher in OECD countries (21% versus 4% in non-OECD countries; IEA, 2012) where nuclear power has been widely deployed since the

1960s in an effort to reduce the import dependency on fossil fuels, diversify the power mix and reduce power system costs.

A key feature of nuclear power is that its electricity generation is virtually carbon-free. Therefore, nuclear power is thought to play a key role in mitigating climate change (IEA, 2012, 2013b). Despite its potential to contribute to the de-carbonization of the power sector, nuclear power is a politically sensitive topic in many countries due to the inherent risk of nuclear accidents and subsequent environmental catastrophes.

The public resentment towards nuclear power has been strongly aggravated in the aftermath of the Fukushima-Daiichi accident, especially in Japan and Europe. Politicians in Japan and Germany reacted rapidly and introduced moratoria on the operation of nuclear power plants in their countries. While discussions about a complete phase-out of nuclear power are still ongoing in Japan, the governments of Germany and Switzerland have already decided to fully abolish the use of nuclear energy by 2022 and 2035, respectively. Nuclear policy was a major topic in the French presidential elections in spring 2012, and several other countries such as Italy, Belgium and the United Kingdom have participated in lively public debates on the future of nuclear power.

With only four nuclear power plants currently under construction and more than 10 GW of existing nuclear plants set to retire in the coming decade (IEA, 2012), nuclear power is losing its share in the European power sector. Maintaining the current level of nuclear power generation, let alone increasing its share in order to reduce the carbon intensity of the power sector, would require several firm investment decisions for new plants by the end of the decade given the long construction time for such plants. Nuclear investments are comparably capital intensive due to the large size of the power station, with the specific investment cost ranging between 3000 to 5000€ /kW – roughly three times more than a typical coal-fired plant and about four times more than a combined-cycle gas turbine (CCGT). Building a nuclear power plant is a long-term investment with the expected lifetime of a station ranging between 50 and 60 years. The capital-intensity of nuclear investments typically requires either a larger cash-flow per output (price spread) or a longer amortization period than an investment in a coal or gas-fired plant. While the former is basically a market risk that all investors in liberalized power markets face, the latter is closely related to political uncertainty. In order to earn money, nuclear power plant operators need to run their plant – and generate cash-flows – for decades. What if nuclear policy mandates a sudden phase-out?

We focus on France in the following as France faces several additional challenges and particularities related to nuclear power. First, nuclear power contributes to roughly 75% of the electricity generation in France, the highest share of nuclear power in electricity generation in the world. Second, most (37 out of 58) French nuclear power plants were built in the time period between 1975 and 1985. Thus, these plants will reach the end of their lifetime between 2025 and 2035 and will need to be either replaced by new plants or retro-fitted via investments in order to prolong their lifetime. Finally, France faces the political challenge of keeping CO_2 emissions from power generation low while public resentment towards nuclear power grows and renewable energies are still too costly and variable to replace base-load technologies on a large scale. Public resentment and recent political debates, such as the one in the presidential elections of 2012, have introduced political uncertainty toward future nuclear policy in France, which could impede investments in nuclear technology and raise system costs.

In our analysis, we focus on three main research questions: First, what are the costs of a nuclear phase-out in France? To this end, we look at two possible phase-out paths (an immediate phase-out and an extended phase-out over 15 years) as well as examine the effect of lifetime prolongations of existing nuclear power plants. Second, who picks up the bill of a nuclear phase-out in France, i.e., will some of the costs be passed down from the French to the rest of the European power system? And third, what is the effect of political uncertainty regarding future French nuclear policy on nuclear power investments and system costs?

In order to address these questions, we apply a stochastic linear programing model of the European power system. The model allows for the calculation of the least-cost dispatch of power plants and investment in new generation technologies across Europe, accounting for power exchange between the individual regions. Additionally, our approach allows us to model uncertainty regarding future nuclear policy in France, i.e., investment decisions are made without knowing *if* and *when* a future government mandates a nuclear phase-out.

We investigate different scenarios of nuclear policy in France. To answer the first two research questions, we compute deterministic benchmark scenarios in which we identify the cost and necessary modifications of the system under perfect foresight, i.e., all investors know what will happen in the future and when. These scenarios are complemented by three stochastic cases that vary in the probability (high, low and medium) of a phase-out decision in the time up to 2050. In these scenarios, the investors in nuclear power have information about the probability of a nuclear phase-out at any given time. The uncertainty about future nuclear policy leads to different investment decisions and system costs compared to the deterministic cases, allowing us to answer our third research question.

The findings of our analysis are manifold: We find that complying with a phase-out of nuclear power leads to higher system costs in France. The additional costs of a nuclear phase-out depend strongly on how the phase-out policy is designed, totaling a maximum of 76 billion €$_{2010}$[26] (which is roughly 2.5% of GDP in France in 2012).[27] Costs are generally highest if the phase-out is immediate, i.e., nuclear plants are required to shut down immediately after the decision is made, not allowing for a transitory period. Regarding our second research question, we find that the costs of a nuclear phase-out are mainly borne by the French power generators. A phase-out reduces infra-marginal rents in the French system as base-load plants with low marginal costs that have fully recovered their investment expenditure are replaced by plants with higher marginal costs (or imports), while the price-setting plants are hardly affected. Neighboring countries are also affected by a French phase-out. A French phase-out leads to higher conventional power production and stronger investments in conventional power plants in the rest of Europe. Concerning the third research question, we find that costs of uncertainty are rather small in the scenarios, reaching a maximum of 6 billion €$_{2010}$. The costs of uncertainty are mitigated by allowing for lifetime-prolonging investments. Moreover, costs of uncertainty may be mitigated if phase-out policies allow for a transitory period. Political uncertainty typically reduces investments in nuclear power; yet find that additional lifetime-prolonging investments are a rational choice under uncertainty. Such investments are not as capital-intensive and are therefore to a lesser degree exposed to the risk of a phase-out harming the economic viability of the investment.

Our analysis bears relevant implications for policy makers who are often confronted with demands for long-term commitments. In addition to in most cases being unrealistic and probably even undesirable from an information-theoretic point of view as it would require the neglecting of future information, our analysis shows that at least in our application a lack of commitment does not come at a high cost.[28]

The paper is structured as follows: Section 5.2 provides an overview of the related literature. Section 5.3 describes the applied approach; Section 5.4 explains the most important technical and political assumptions. Scenario results for France and the rest of Europe are discussed in Section 5.5. Section 5.6 concludes.

5.2 Literature Overview

Several recent scientific publications have analysed nuclear policy and nuclear phase-out scenarios for different countries. For instance, Kannan and Turton (2012) analyze

[26]€$_{2010}$ denotes real Euros based on 2010 values.

[27]An absolute labelling of such cost figures is difficult as it would require an assessment of the risk-costs of nuclear power plant operation, for which there is no reliable data available.

[28]Under asymmetric information, similar reasoning applies. As shown by Höffler and Wambach (2013) in an application to infrastructure investments, regulators face a trade-off between early commitment and the aim to elicit information in later stages of the game.

options for the Swiss power system to replace nuclear power. They find that in the short-term, newly built gas-fired capacity can meet electricity demand cost-effectively, in the medium and long-term nuclear power is the most cost effective solution. Park et al. (2013) show that a Sustainable Society scenario, which focuses on demand management and renewable electricity, improves energy security and reduces more emissions at affordable cost in Korea as compared to two scenarios which focus on nuclear expansion. Hong et al. (2013) use a multi-criteria decision-making analysis to assess the potential impacts of four different energy policy pathways in Japan. Taking into account economic, environmental and social criteria, they find that a nuclear-free pathway for Japan is the worst option to pursue. Fürsch et al. (2012a) analyze costs of a nuclear phase-out in Germany. They find that in a scenario similar to the actual German phase-out plan, these costs amount to 16 billion € for the German power sector.

Several studies analyzing nuclear and energy policy *in France* have been published: RTE (2011) identifies the risks of an imbalance between electricity demand and supply within a timeframe up to 2030. The authors apply a probability-based simulation model and compare scenarios with different shares of nuclear generation in the electricity mix; however, none with a full phase-out from nuclear power.

CAS (2012) analyzes four different scenarios for nuclear power plant operation in France ranging from an immediate exit from nuclear generation to a continued use of the technology. In summary, the authors calculate the cost of an immediate exit from nuclear power to amount to about 100 billion € in the timeframe between 2010 and 2030.

CDC (2012) assesses all costs of nuclear power generation in France presenting past, present and future costs. Concerning future costs of nuclear, the study compares four scenarios with different assumptions regarding nuclear power generation in France.

UFE (2011) analyzes different possible policy choices based on climate, social, economic and financial criteria. The authors compare three scenarios with different shares of nuclear generation in the period up to 2030. In a scenario with 20% nuclear generation, the authors calculate a required investment expenditure of 434 billion €.

As we show in the following, our results are generally in line with previous results presented in the literature. A difference in the magnitude of the results can be explained by the different scenario assumptions, research focus and methodology applied. Our approach contributes to the existing stream of literature in at least three ways: First, our scenario definition is novel to the literature since it systematically highlights the effects of different phase-out periods and lifetime prolongations. Second, we draw attention to the distribution of costs between the French and the European power system.

And third, we incorporate a new type of uncertainty into the literature, namely political uncertainty regarding nuclear policy, and rigorously analyze its effect on costs and investment behavior.

5.3 Methodology

Previous research on uncertainty in energy markets has focused primarily on uncertainty with respect to demand evolution (e.g., Gardner, 1996, Gardner and Rogers, 1999), fuel and CO_2 price development (e.g., Patino-Echeverri et al., 2009, Roques et al., 2006), portfolio and risk management (e.g., Gröwe-Kuska et al., 2003, Morales et al., 2009) and renewables expansion, both regarding short-term (e.g., Nagl et al., 2012, Sun et al., 2008, Swider and Weber, 2006) and long-term uncertainties (e.g., Fürsch et al., 2012b).

Our approach, in contrast, focuses on long-term uncertainties associated with nuclear policy in France. In doing so, we employ a stochastic linear programing model of the European power system. Given a set of input parameters and constraints, the model calculates dispatch and investment decisions in such a way that residual electricity demand is satisfied and total *expected* discounted system costs in the European power system are minimized.[29] Uncertainty enters the model in the form of whether or not there is a nuclear phase-out decision in France at a particular point in time.[30]

Incorporating uncertainty in a deterministic investment and dispatch model typically influences model results. Informally speaking, while in the deterministic setting the social planner has perfect foresight and can optimally adjust decisions according to his single view of the world, in the multistage stochastic setting the social planner has to make decisions taking several different states of the world into account. This usually leads to deviations from the deterministically-optimal decisions and thus to increasing costs. In our analysis, we quantify these deviations and interpret their implications.

The timeframe of our analysis is up to 2050 in five-year steps. In order to derive consistent investment decisions throughout the outlook period, the optimization is extended to 2070. The dispatch in each modeled year is represented by three representative days per season consisting of six time-slices taking into account load and renewable generation. Investments take place on an annual granularity.

[29] Residual demand refers to the demand met by conventional generation. It is equivalent to total demand minus generation from renewables (RES-E).

[30] The model is a stochastic extension of the deterministic linear programing model DIME and its successor DIMENSION. Bartels (2009) and Richter (2011) provide detailed descriptions of DIME and DIMENSION including all model equations. The deterministic model has been successfully applied in electricity market modeling, as for instance in Jägemann et al. (2013) in the modeling of renewable and carbon policies or in the modeling of flexibility options in Bertsch et al. (2015). The stochastic extension is straightforward and implemented as discussed in Shapiro et al. (2009).

Nuclear phase-out decisions in France (denoted “D” in Figure 5.1) can occur in every five-year time interval between 2015 and 2035 (mimicking the legislative period of the French government). We assume that no phase-out decision can be made after 2035 in order to have consistent and comparable results for the time period up to 2050. Moreover, this simplification also helps to reduce computer runtime.[31] We thus consider four states, denoted by State 1 (phase-out decision between 2015 and 2020) to State 4 (phase-out decision between 2030 and 2035), in which a phase-out from nuclear power in France occurs as well as an additional state without a phase-out, denoted by State 5. Obviously, we do not allow for investments in nuclear power in France after a phase-out decision has been made.

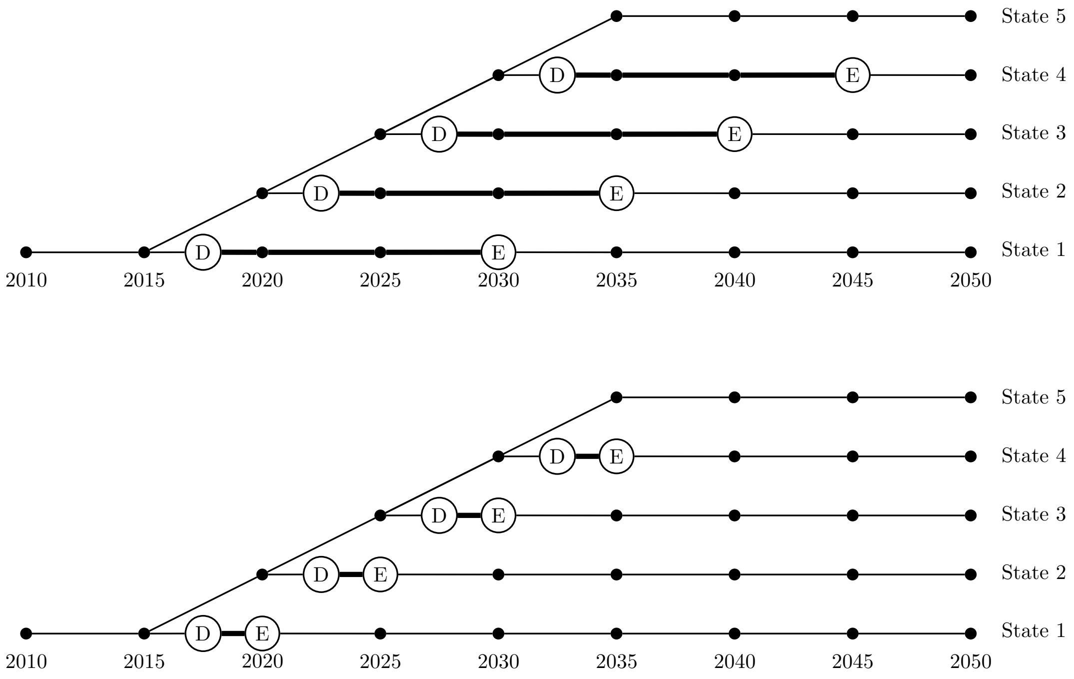


Figure 5.1: Scenario trees for an extended and an immediate exit from nuclear power in France

The benchmark scenarios (denoted by “exit_2020”, “exit_2025”, “exit_2030”, “exit_2035” and “no_exit” in Table 5.1) are deterministic cases in which we identify the costs and necessary modifications of the system under perfect foresight, i.e., all investors know what will happen in the future and when. These scenarios are complemented by three stochastic cases that vary in the probability of a phase-out decision during the time up to 2050 (denoted by “high_prob”, “low_prob” and “medium_prob” in Table 5.1).

[31] The model is implemented in GAMS and solved using CPLEX. Solving the model on an Intel(R) Xeon(R) (2 processors, each 2.67 GHz) with 96.0 GB RAM takes on average (depending on the scenario setting) between 12 and 24 hours.

We perform two sensitivity analyses: The first deals with the *form* of the phase-out decision, i.e., whether the phase-out/exit (denoted by "E" in Figure 5.1) takes place *immediately* after the decision or *over an extended* period of 15 years (see Figure 5.1). The second sensitivity analysis introduces the possibility of a prolongation of lifetimes of existing nuclear power plants in France. In the sensitivity analysis, lifetimes of existing French nuclear power plants can be prolonged beyond their license period of 40 years. In order to fulfill the required safety standards for a lifetime prolongation, significant investments have to be made. Previous studies have estimated additional costs for a prolongation of nuclear power plant lifetimes by another 20 years in France to amount to 55 billion € (Lundgren and Patel, 2012). Based on these figures, we estimate nuclear retrofit costs in France to amount to 870 €$_{2010}$/kW. By way of comparison, the German government in 2010 assumed retrofit costs for existing nuclear power plants in Germany of 500 €/kW for a lifetime prolongation of 20 years (Prognos, 2010).

We use the following abbreviations for our model runs: "15y w/o prolongation" indicates the upper scenario tree without the option for prolongation of existing nuclear power plants in France; "15y prolongation" indicates that we allow for prolongation. Abbreviations for the lower scenario tree are defined analogously.

Table 5.1: Probabilities of the different states in the model runs

	State 1	State 2	State 3	State 4	State 5
high_prob	0.05	0.05	0.05	0.05	0.80
medium_prob	0.125	0.125	0.125	0.125	0.5
low_prob	0.2	0.2	0.2	0.2	0.2
exit_2020	1	0	0	0	0
exit_2025	0	1	0	0	0
exit_2030	0	0	1	0	0
exit_2035	0	0	0	1	0
no_exit	0	0	0	0	1

5.4 Data and Assumptions

The main parameter assumptions entering the model are demand development, fossil fuel and CO_2 prices, technical and economic parameters of the power plants (in particular, investment and retrofit costs) as well as the development of renewable power deployment. The presentation of data in this section is based on the assumptions in Fürsch et al. (2012a) and Prognos (2010).

5.4.1 Electricity demand

We assume a slightly increasing electricity demand in France, rising to 543 TWh_{el} in 2030 and decreasing moderately decrease to 522 TWh_{el} in 2050, predominantly driven by the uptake of energy efficiency measures (see Table 5.2). Concerning the rest of Europe, we assume moderate growth rates of on average 0.9% p.a. between 2010 and 2050, resulting in a net electricity demand in the modeled regions (excluding France) of 3089 TWh_{el} in 2050.[32]

Table 5.2: Net electricity demand in TWh_{el} in France and Europe (excluding France)

	2010	2020	2030	2040	2050
France	501	513	543	533	522
Europe (excl. France)	2161	2455	2666	2871	3089

5.4.2 Fuel and CO_2 prices

Fuel prices for power plants are based on international market prices plus transportation costs to the power plants (see Table 5.3). Prices for hard coal and natural gas are assumed to increase in the long run up to 14.2 €$_{2010}$/MWh_{th} and 31.6 €$_{2010}$/MWh_{th}, respectively.

CO_2 prices are assumed to be the same in all model runs and states. They are assumed to increase in the long run up to 75.1 €$_{2010}$/t CO_2 in 2050 from 23.9 €$_{2010}$/t CO_2 in 2020.

Table 5.3: Fuel costs in €$_{2010}$/MWh_{th} and CO_2 prices in €$_{2010}$/t CO_2

	2010	2020	2030	2040	2050
Coal	11.0	10.1	10.9	11.9	14.2
Natural gas	17.0	23.1	25.9	28.8	31.6
Oil	39.0	47.6	58.0	69.0	81.4
CO_2	14.0	23.9	41.3	58.7	75.1

5.4.3 Technical and economic parameters for power plants

We assume the introduction of several new or improved conventional technologies as well as decreasing investment costs over time due to learning effects (see Table 5.4).

[32]The modeled regions cover France, the United Kingdom, Spain, Portugal, Italy, Germany, Austria, Switzerland, Belgium, the Netherlands, Poland, the Czech Republic and Denmark-West.

Table 5.4: Specific investment costs for thermal power plants in €$_{2010}$/kW

	2020	2030	2040	2050
Nuclear	3,000	3,000	3,000	3,000
Coal	1,300	1,300	1,300	1,300
Coal (innovative)	2,250	1,875	1,700	1,650
CCGT	950	950	950	950
OCGT	400	400	400	400
IGCC-CCS	-	2,039	1,986	1,782
CCGT-CCS	-	1,173	1,133	1,020
Coal-CCS	-	1,848	1,800	1,752
Coal -CCS (innovative)	-	2,423	2,263	2,102

5.4.4 Development of RES-E

RES-E development is treated exogenously in our analysis and is not optimized over time within the model. We assume a strong expansion of RES-E generation in France, reaching 277 TWh in 2050 up from 152 TWh in 2020 and 85 TWh in 2010 (see Table 5.5). This expansion is driven mainly by photovoltaics and wind power technologies. RES-E development is assumed to be the same in all model runs and states.

For the other European countries, we assume a continuous increase of RES-E generation within the coming decades. This development is driven by an increased deployment of wind farms, mainly in Denmark, the United Kingdom, Poland and the Netherlands. Electricity generation from photovoltaics increases primarily in Southern Europe, and geothermal energy is assumed to play an important role for electricity generation only in Italy because of its potential for high enthalpic resources. In 2050, RES-E generation in the European countries accounted for in this analysis (excluding France) is assumed to amount to 1616 TWh compared to approximately 797 TWh in 2020.

Table 5.5: Development of RES-E generation in France in TWh

	2010	2020	2030	2040	2050
Hydro	53	56	56	56	56
Wind onshore	14	47	94	104	100
Wind offshore	0	25	35	40	66
Photovoltaics	1	6	19	28	35
Biomass + Waste	17	17	17	17	17
Geothermal	0	1	3	3	3
Total	85	152	224	247	277

5.5 Results and Discussion

In Subsections 5.5.1 and 5.5.2, we present the deterministic costs of a phase-out from nuclear power in France and the effect on costs across the rest of the European power system. Subsection 5.5.1 specifically deals with the costs of prohibiting the prolongation of lifetimes of existing nuclear power plants in France. Furthermore, in Subsection 5.5.2, we look at the cost differences between a deterministic phase-out scenario (i.e., "exit_2020" to "exit_2035") and a deterministic scenario with nuclear power available in France until 2050 (i.e., "no_exit"). These values reflect the costs of having to substitute nuclear power plants in France with other conventional fossil-fueled power technologies in France and Europe under perfect foresight. In Subsection 5.5.3, in order to better assess the effects of uncertainty on costs, we analyze the impact of uncertainty on investment behavior in nuclear power plants in France. Subsection 5.5.4 explores the effect of uncertainty on system costs. Costs of uncertainty are given in our analysis by comparing a stochastic scenario state to the corresponding deterministic scenario (e.g., cost differences between State 3 in model run "high_prob" and the deterministic model run "exit_2030"). These costs reflect the inefficiency that is arising in the system due to political uncertainty.

5.5.1 The cost of prohibiting the prolongation of nuclear power plant lifetimes in France

The costs of prohibiting lifetime prolongations for existing nuclear power plants in France are significant. In a scenario without phase-out, these costs amount to 19 billion €$_{2010}$ and are mainly driven by higher investment costs as well as higher import costs/lower export revenues (see Figure 5.2).[33] The former is due to the lack of comparably low-cost nuclear lifetime prolongations which, if available, would reduce investment needs in newly built capacity, particularly newly built base-load capacity (e.g., nuclear), in the intermediate term in France. Note that not all nuclear capacity reaching the end of its licensing period is replaced by newly built (nuclear or other fossil fuel) capacity in France in the scenario without lifetime prolongations. Therefore, power generation in France is lower than in the scenario allowing for lifetime prolongations, resulting in lower exports and higher imports.

Additional system costs in the European power system (including France) amount to 20 billion €$_{2010}$ and are, as seen in the previous results, of the same magnitude as additional costs in France. This reveals that costs are hardly passed from the French to the rest of the European system, i.e., France has to accept the financial burden of prohibiting lifetime prolongations. European costs are mainly driven by higher investment costs (primarily due to higher investment costs in France) and, in addition, by higher variable

[33]Costs refer to the discounted costs for the whole power system and for the French power system, accumulated over the time horizon up to 2050. A discount rate of 10% has been assumed.

costs due to an increased utilization of conventional power plants in the rest of Europe (see middle bar in Figure 5.2).

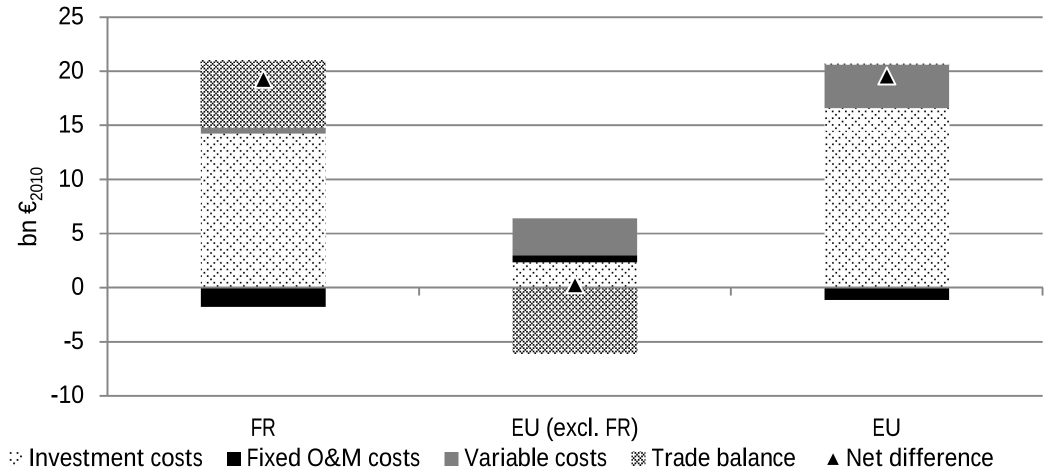


Figure 5.2: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – w/o prolongation vs. prolongation

5.5.2 The deterministic costs of a nuclear phase-out in France

The French power system can adapt to a phase-out from nuclear power at the expense of higher system costs in France and Europe (see Figures 5.3 to 5.6). The cost differences in this subsection reflect the costs of having to substitute (cost competitive) nuclear power plants in France with other conventional fossil-fueled power technologies in France and Europe under perfect foresight.

Additional (deterministic) costs in France of a phase-out can be significant, amounting to 76 billion €$_{2010}$ in a scenario with an immediate nuclear phase-out in 2020 compared to a scenario without nuclear phase-out and the possibility of prolonging the lifetime of existing nuclear plants (see Figure 5.6).

Deterministic cost differences in France are mainly driven by higher variable costs due to increased utilization of existing and newly built fossil-fueled power plants as well as a reduction in export revenues/higher import costs. The latter is due to lower exports and higher imports (in particular, from Germany) as not all phased-out nuclear generation is replaced by other generation technologies within France. Investment costs are lower in phase-out scenarios without prolongation opportunities due to the non-availability of nuclear power plant investments. Nuclear power plants, with comparably high investment costs, are in part replaced by other fossil-fueled power plants. Investment costs are typically higher in phase-out scenarios with prolongation opportunities, indicating that

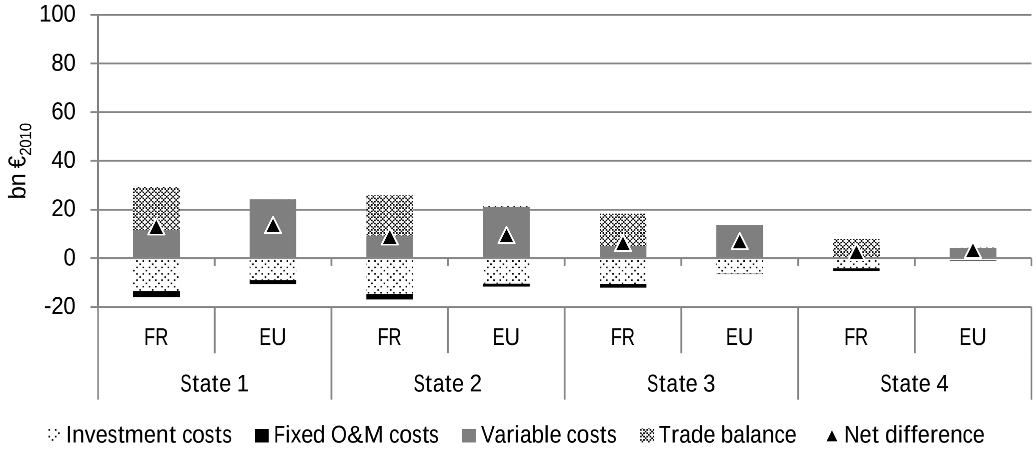


Figure 5.3: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 15y w/o prolongation

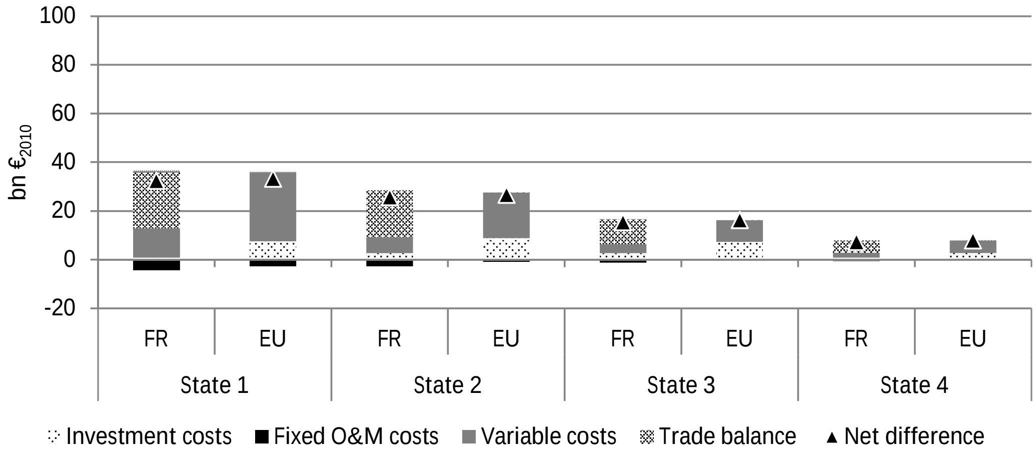


Figure 5.4: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 15y prolongation

nuclear capacity is prolonged even though it has to be replaced by newly built (fossil fuel) capacities after the phase-out.

Additional (deterministic) costs in the European system (including France) of a French nuclear phase-out are incurred to a large extent by the French power system, with only a small fraction being passed onto the rest of the power system (see Figures 5.3 to 5.6).[34] Additional costs in the European system are mainly driven by higher variable costs due to the non-availability of low-cost nuclear power in France. Conventional fossil-fueled power plants are utilized more often in France and the rest of Europe leading to higher CO_2 emissions in the European power system. Total investment costs in Europe

[34]In the figures shown in this subsection as well as the following, we refrain from showing the cost components for Europe excl. France for better readability since the cost components follow a similar pattern to the one displayed in Figure 5.2. For the stochastic cases, data may be found in Appendix D.

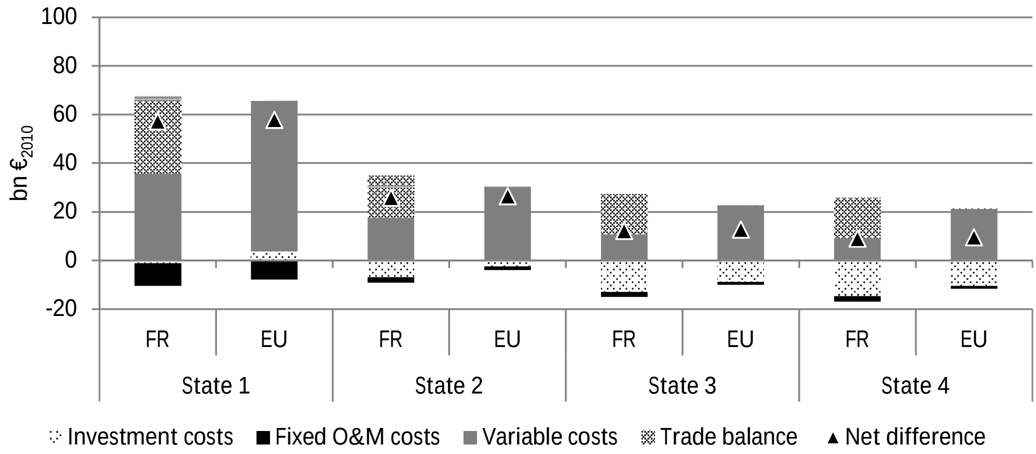


Figure 5.5: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 0y w/o prolongation

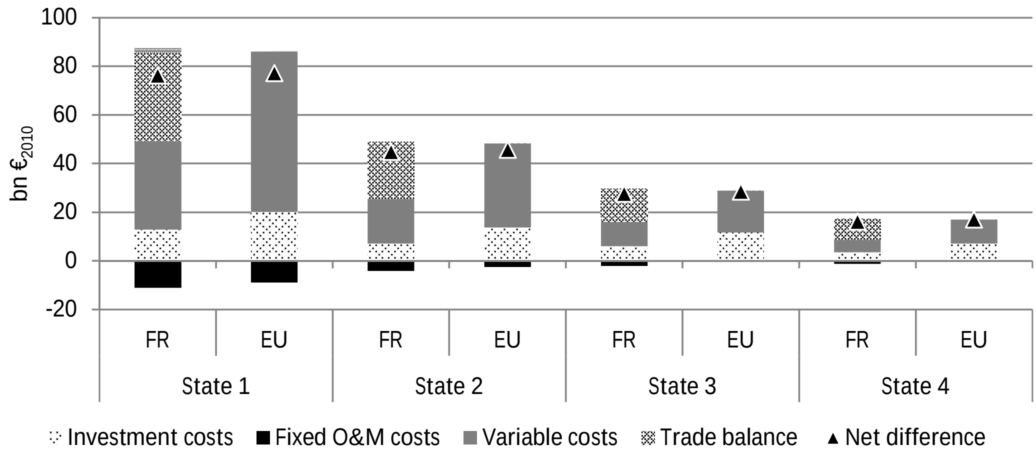


Figure 5.6: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Deterministic cost difference – 0y prolongation

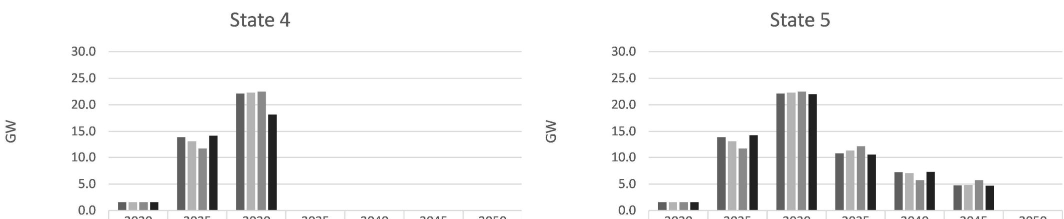
follow a similar pattern as the one described above for the French system, i.e., total investment costs are typically lower in the case of no prolongation opportunities and higher otherwise.

We find that deterministic cost differences in France and Europe follow two main patterns: First, they are clearly higher under an immediate phase-out (see Figures 5.5 and 5.6) compared to a scenario with a prolonged phase-out (see Figures 5.3 and 5.4). Second, the later the phase-out occurs, the stronger the reduction in system cost differences will be. The first point bears a clear policy implication: Policy makers are well-advised to opt for extended phase-out periods if a phase-out is to be introduced. Additional costs are substantially lower in this case.

5.5.3 Investment in nuclear power under uncertainty

We observe significant deviations from deterministically socially-optimal investments under uncertainty. Intuitively speaking, one would expect over-investment in nuclear power and under-investment in alternative base-load technologies under uncertainty in states with an early phase-out. Analogously, intuition suggests that uncertainty leads to under-investment in nuclear power in states with either no or a late phase-out. However, deviations from this intuition are possible due to the possibility of prolonging the lifetimes of existing nuclear power plants in certain model runs. Obviously, the high number of model runs computed does not allow for a discussion of all arising patterns. Figures 5.7 to 5.10 therefore illustrate the typical investment patterns that may arise and that help to clarify the system cost effects described in the next subsection.

Uncertainty may lower investments in new nuclear capacity in 2025 for scenario states with either no or a late nuclear phase-out (i.e., States 4 or 5) under a setting with no possible lifetime prolongations. In the example presented in Figure 5.7, this in turn leads to catch-up effects after 2030 once the uncertainty (in the model) has been resolved. The level of this effect is correlated to the probability of a phase-out occuring, i.e., investments in 2025 are lower in the model run "high_prob" than in "low_prob", followed by a more pronounced catch-up effect in "high_prob" than in "low_prob".



State 4

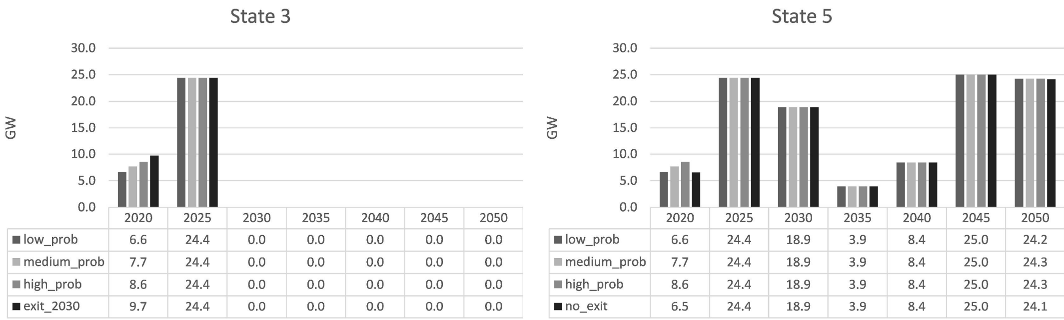
	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	13.9	22.1	0.0	0.0	0.0	0.0
medium_prob	1.6	13.1	22.3	0.0	0.0	0.0	0.0
high_prob	1.6	11.8	22.5	0.0	0.0	0.0	0.0
exit_2035	1.6	14.2	18.2	0.0	0.0	0.0	0.0

State 5

	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	13.9	22.1	10.8	7.2	4.7	0.0
medium_prob	1.6	13.1	22.3	11.3	7.1	4.8	0.0
high_prob	1.6	11.8	22.5	12.2	5.7	5.7	0.0
no_exit	1.6	14.3	22.0	10.5	7.3	4.7	0.0

Figure 5.7: Investment in nuclear power in France in GW: 15y w/o prolongation

Allowing for lifetime prolongations, a greater amount of existing nuclear capacity may be prolonged under uncertainty in scenario states with either no or a late nuclear phase-out (see State 5 in Figure 5.8). Less nuclear capacity is typically retrofitted under uncertainty in scenario states with an early phase-out (see State 3 in Figure 5.8). The investments in 2020 are basically retrofit investments in existing nuclear capacity, with 1.6 GW being newly-built capacity. Here, the nuclear power plant Flamanville is assumed to be online in the model. New nuclear power plants are only built in State 5 after 2040. Remarkably, the increase in retrofit investments in 2020 in State 5 appears to have no effect on new nuclear power plant investments or retrofit investments thereafter.



State 3 (GW):

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	24.4	0.0	0.0	0.0	0.0	0.0
medium_prob	7.7	24.4	0.0	0.0	0.0	0.0	0.0
high_prob	8.6	24.4	0.0	0.0	0.0	0.0	0.0
exit_2030	9.7	24.4	0.0	0.0	0.0	0.0	0.0

State 5 (GW):

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	24.4	18.9	3.9	8.4	25.0	24.2
medium_prob	7.7	24.4	18.9	3.9	8.4	25.0	24.3
high_prob	8.6	24.4	18.9	3.9	8.4	25.0	24.3
no_exit	6.5	24.4	18.9	3.9	8.4	25.0	24.1

Figure 5.8: Investment in nuclear power in France in GW: 15y prolongation

Investment levels may be much higher under uncertainty than what is considered to be deterministically socially optimal. In State 4 in Figure 5.9, investment levels at the social optimum under uncertainty are between investments in the model runs "exit_2035" and "no_exit".[35] Investments in the "low_prob" model run thus amount to 11.4 GW in 2025 and 22.3 GW in 2030 compared to no investment in "exit_2035". The maximum difference in State 5 is achieved in the years 2025 and 2030, at which time we see no investments in nuclear power plants in France in "high_prob" compared to the deterministically socially-optimal levels of 14.3 GW in 2025 and 22.0 GW in 2030 in "no_exit".

State 4 (GW):

	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	11.4	22.3	0.0	0.0	0.0	0.0
medium_prob	1.6	6.8	21.3	0.0	0.0	0.0	0.0
high_prob	1.6	0.0	0.0	0.0	0.0	0.0	0.0
exit_2035	1.6	0.0	0.0	0.0	0.0	0.0	0.0

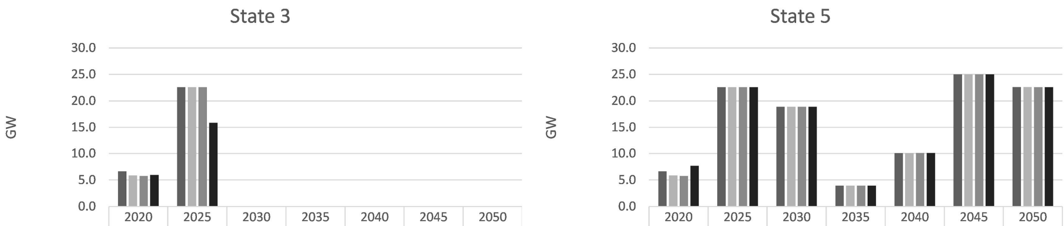
State 5 (GW):

	2020	2025	2030	2035	2040	2045	2050
low_prob	1.6	11.4	22.3	13.0	5.2	6.2	0.0
medium_prob	1.6	6.8	21.3	18.3	3.5	6.6	0.8
high_prob	1.6	0.0	0.0	25.0	9.5	11.4	0.8
no_exit	1.6	14.3	22.0	10.5	7.3	4.7	0.0

Figure 5.9: Investment in nuclear power in France in GW: 0y w/o prolongation

Figure 5.10 illustrates investment patterns under uncertainty with prolongation opportunities. Allowing for the prolongation of existing nuclear capacity, more capacity lifetimes are prolonged in State 3 in the "low_prob" case due to the high investment levels in "no_exit". However, with higher probability of phasing-out, even less capacity is prolonged in State 3 in "high_prob" than in "exit_2030".

[35] Higher investment levels in 2030 compared to the "no_exit" level are again due to catch-up effects.



State 3:

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	22.6	0.0	0.0	0.0	0.0	0.0
medium_prob	5.9	22.6	0.0	0.0	0.0	0.0	0.0
high_prob	5.7	22.6	0.0	0.0	0.0	0.0	0.0
exit_2030	5.9	15.9	0.0	0.0	0.0	0.0	0.0

State 5:

	2020	2025	2030	2035	2040	2045	2050
low_prob	6.6	22.6	18.9	3.9	10.1	25.0	22.6
medium_prob	5.9	22.6	18.9	3.9	10.1	25.0	22.6
high_prob	5.7	22.6	18.9	3.9	10.1	25.0	22.6
no_exit	7.7	22.6	18.9	3.9	10.1	25.0	22.6

Figure 5.10: Investment in nuclear power in France in GW: 0y prolongation

5.5.4 Costs of uncertainty

Costs of uncertainty are given by comparing a stochastic scenario state to the corresponding deterministic scenario. Due to the large number of calculations performed, we only show selected results in this subsection. Cost figures for all model runs can be found in Appendix D.

Costs of uncertainty in France and Europe are rather small in most model runs and states. In fact, costs can amount to 6 billion €$_{2010}$ in a setting with a high probability of a phase-out and no possibility of prolongation for existing nuclear power plants (see model run "high_prob" in Figure 5.11).

Costs of uncertainty in France in the case of no phase-out from nuclear power and a setting without prolongation opportunities are to a large extent driven by a change in the trade balance (i.e., lower export revenues and higher import costs) and lower investment costs (see Figures 5.11 and 5.12). The effect concerning variable costs is not unique: While variable costs are higher under uncertainty in model run "high_prob" in Figure 5.11, they are lower in "low_prob" and "medium_prob".

Costs of uncertainty in France follow two main patterns: First, costs are typically lower in scenarios with an extended phase-out period of 15 years than in scenarios with an immediate phase-out from nuclear power (compare Figures 5.11 and 5.12). Second, costs of uncertainty typically increase with increasing probability of a phase-out in states with either no or a late phase-out (see Figure 5.11). Similarly, costs of uncertainty increase with decreasing probability of phasing-out in states with an early phase-out (see Figure 5.13).

Costs of uncertainty for the European power system (including France) follow similar patterns. Costs are typically lower in scenarios with an extended phase-out period. Additional costs are mainly caused by higher variable costs under uncertainty in the case of either no or a late phase-out without the possibility of lifetime prolongations (see

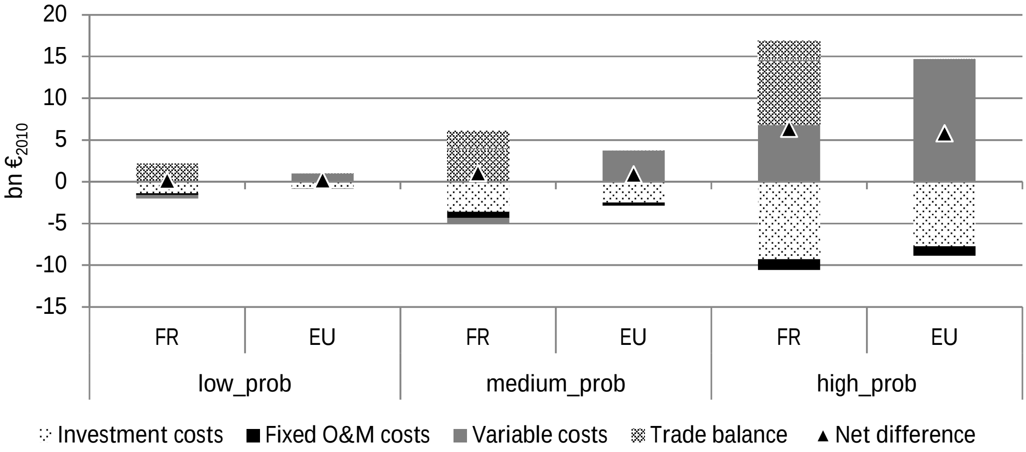


Figure 5.11: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y w/o prolongation – State 5

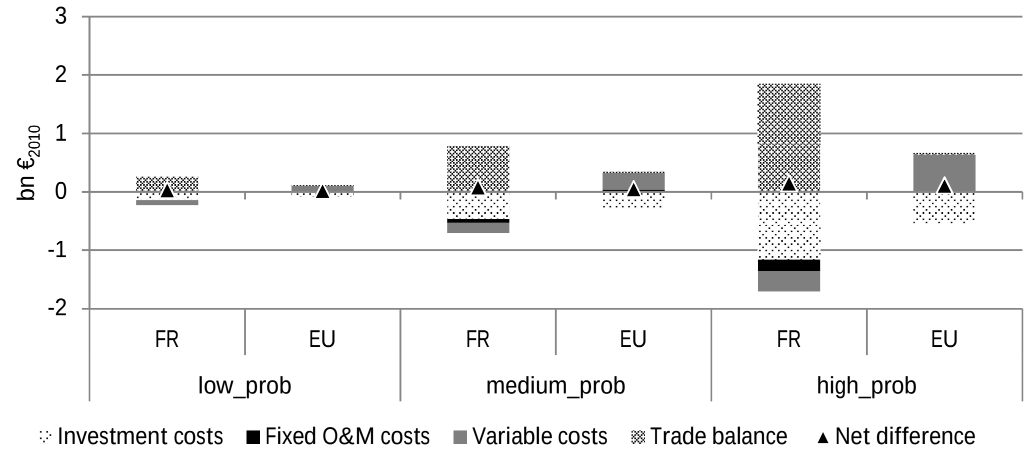


Figure 5.12: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y w/o prolongation – State 5

Figures 5.11 and 5.12). When allowing for prolongation, the effect concerning variable and investment costs is ambiguous. For instance, investment costs may be higher in the case of an early phase-out (see Figure 5.14) due to over-investment in nuclear power plants in France, as illustrated in Figure 5.10. However, lower investment costs are also possible in the case of an early phase-out (see Figure 5.13) due to fewer prolongations of existing nuclear power plant lifetimes under uncertainty.

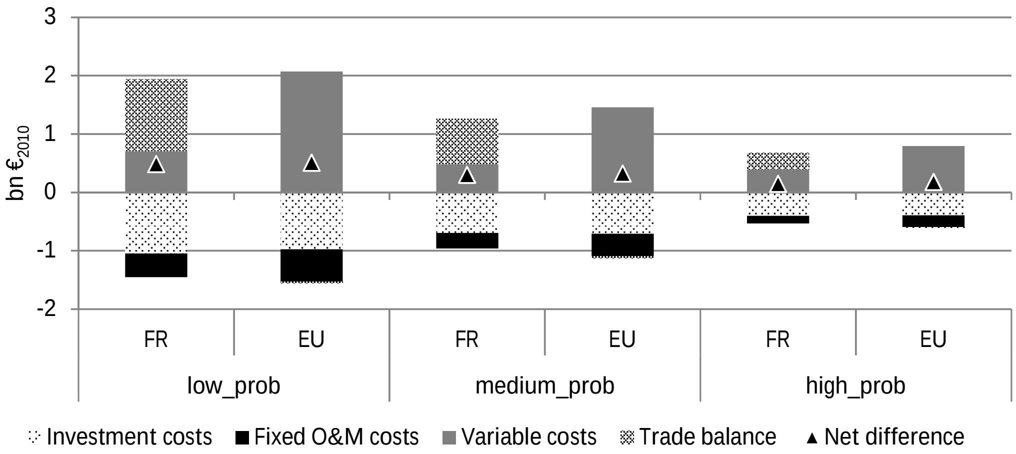


Figure 5.13: Accumulated (discounted) system cost differences differentiated by cost categories in bn $€_{2010}$ (2010-2050): Cost of uncertainty – 15y prolongation – State 2

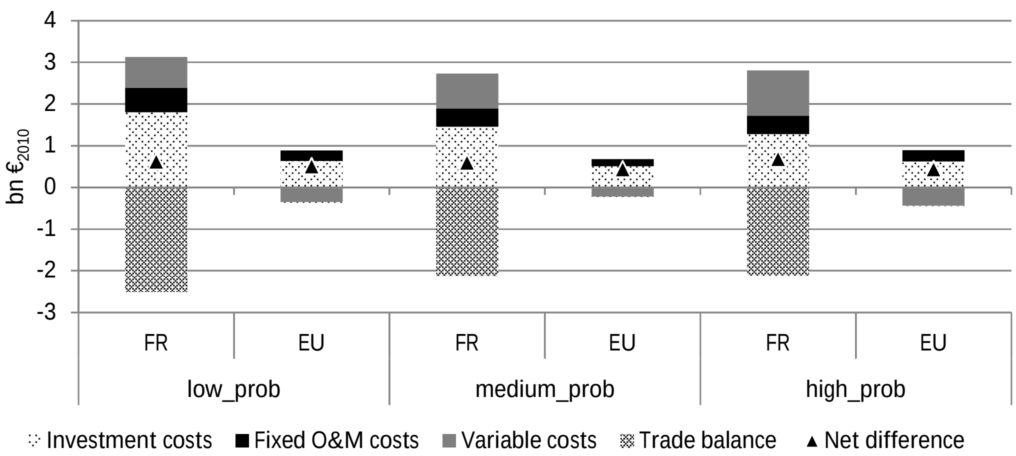


Figure 5.14: Accumulated (discounted) system cost differences differentiated by cost categories in bn $€_{2010}$ (2010-2050): Cost of uncertainty – 0y prolongation – State 3

5.6 Conclusion and Policy Implications

This paper provides a model-based analysis of the possible future role of nuclear power in France. We have investigated different scenarios of nuclear policy in France, both under perfect foresight and under uncertainty. We have shown that a phase-out from nuclear power in France leads to higher system costs in the power sector. These costs are mainly borne by the French system, and the cost effects for the rest of the European power system are rather limited.

Our finding that extended phase-out periods lead to lower costs is in line with the examples of Belgium and Switzerland as these countries have opted for extended phase-out periods. Furthermore, our analysis suggests that the costs of uncertainty are surprisingly low when compared to the costs of phasing out. Further, supported by information theoretic arguments, this finding presents a strong case, at least in this application, against a long-term commitment by policy makers to future nuclear policy.

Further research could address the full costs of nuclear power operation. Such an analysis should include an investigation of the risk-costs of nuclear power plant operation. A further promising research avenue may be the investigation of the possible additional burden of a phase-out for different consumer groups in France and Europe. Bearing in mind that most of the heating in France is electricity based, rising wholesale prices for electricity as a result of increasing system costs in France are of particular political and social relevance. We emphasize that our analysis could also be applied to other forms of political uncertainty such as government intervention in the market through support schemes for renewables, capacity markets or the introduction/extension of CO_2 cap-and-trade schemes.

Appendix A

Supplementary Material for Chapter 2

A.1 Econometric Appendix

Wald test of perfect competition

As proposed by Ellis and Halvorsen (2002), we test our results regarding market power exertion against a null hypothesis of perfectly competitive price-taking behavior. Within our framework, perfect competition corresponds to $\beta_0 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$. We test the rejection of this null hypothesis using a Wald test. The resulting mean of the test statistic is found to be 36.492 (std. dev. 4.701). With a critical value 15.09, we reject the hypothesis of perfectly competitive behavior at the 1%-level.

Polynomial representation of $\beta(t)$

We estimate the Model 1 system of equations with five different polynomial representations of the time-varying mark-up. The specifications are as follows:

- Scalar representation: $\beta(t) = \beta_0$
- Linear representation: $\beta(t) = \beta_0 + \beta_1 T$
- Quadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2$
- Cubic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$
- Biquadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4$

The estimation for the first four models are given in Table A.1 (scalar representation), Table A.2 (linear representation), Table A.3 (quadratic representation), Table A.4 (cubic representation) and Table 2.5 (biquadratic representation).

The results clearly show that the polynomial in $\beta(t)$ is only statistically significant for higher order approximations. Apart from that, almost all other estimates are relatively robust for different specifications. Therefore, we use the biquadratic specification as it reflects a higher order Taylor-approximation to the actual $\beta(t)$-function.

Table A.1: Scalar repr.: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.719	0.034	7.35E-38***	4.01E-37	0.103	7.31E-3
α_Q	3.03E-8	3.20E-9	7.10E-10***	4.47E-10	2.98E-9	2.51E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.32E-5	2.96E-54***	1.37E-54	1.08E-4	1.99E-6
α_E	2.144	0.100	2.53E-10***	7.34E-10	0.186	0.019
α_S	-0.187	0.136	0.195	0.228	0.114	0.038
γ_{KK}	-6.43E-4	2.78E-4	0.133^{+}	0.141	3.39E-4	3.73E-5
γ_{QQ}	3.47E-8	2.72E-9	9.30E-4***	6.76E-4	8.96E-9	8.34E-10
γ_{EE}	1.208	0.266	0.077*	0.096	0.591	0.105
$\gamma_{KQ} = -\gamma_{LQ}$	-8.70E-9	2.74E-9	0.198	0.119	6.06E-9	5.78E-10
$\gamma_{KE} = -\gamma_{LE}$	2.33E-3	6.35E-5	9.04E-10***	1.23E-9	2.30E-4	9.38E-6
γ_{QE}	-4.17E-8	4.20E-9	3.50E-7***	2.33E-7	5.84E-9	5.03E-10
β_0	5.276	4.253	0.199	0.233	2.725	0.221
τ_{MFM}	26.427	8.941	0.567	0.124	44.715	2.824
τ_{CAP}	70.925	40.873	0.633	0.169	139.993	8.118
ϱ_{LAU}	18.112	1.778	0.028**	0.012	7.622	0.336
ϱ_{LKZ}	-9.679	4.604	0.279	0.200	7.603	0.408
ϱ_{KAU}	32.773	2.439	0.100^{+}	0.032	18.950	1.059
ϱ_{KKZ}	3.032	0.680	0.602	0.090	5.715	0.352
τ_{INV}	10.810	0.079	3.25E-16***	5.74E-16	0.508	0.030
ϱ_{SAU}	39.729	1.781	1.24E-3***	9.36E-4	10.627	0.638
ϱ_{SKZ}	-7.900	2.813	0.392	0.183	8.634	0.481
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.54 std. dev. 0.05, Eq. (2.21): mean 0.62 std. dev. 0.1, Eq. (2.26): mean 0.27 std. dev. 0.22, Eq. (2.28): mean 0.54 std. Dev. 0.05					

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table A.2: Linear repr.: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	std. dev.	Mean	std. dev.	Mean	std. dev.
α_0	20.720	0.033	1.93E-36***	1.04E-35	0.103	7.22E-3
α_Q	2.92E-8	5.37E-9	1.06E-7***	1.44E-7	3.57E-9	3.84E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.52E-5	3.97E-52***	1.70E-52	1.09E-4	2.00E-6
α_E	2.134	0.090	7.05E-10***	1.78E-9	0.194	0.016
α_S	-0.187	0.136	0.190	0.221	0.114	0.038
γ_{KK}	-6.41E-4	2.73E-4	0.135+	0.144	3.40E-4	3.71E-5
γ_{QQ}	3.25E-8	6.57E-9	5.59E-3***	4.72E-3	1.01E-8	1.11E-9
γ_{EE}	1.244	0.291	0.073*	0.091	0.596	0.103
$\gamma_{KQ} = -\gamma_{LQ}$	-8.09E-9	3.94E-9	0.273	0.173	6.26E-9	8.94E-10
$\gamma_{KE} = -\gamma_{LE}$	2.32E-3	6.09E-5	2.53E-9***	2.51E-9	2.38E-4	6.49E-6
γ_{QE}	-4.01E-8	7.36E-9	6.99E-6***	7.42E-6	6.56E-9	7.76E-10
β_0	3.991	6.864	0.341	0.324	3.419	0.337
β_1	-0.073	0.151	0.511	0.222	0.204	0.022
τ_{MFM}	26.308	8.868	0.565	0.127	44.434	3.545
τ_{CAP}	74.217	43.037	0.624	0.169	141.053	9.315
ϱ_{LAU}	17.868	1.996	0.031**	0.013	7.598	0.387
ϱ_{LKZ}	-9.040	6.017	0.328	0.239	7.570	0.480
ϱ_{KAU}	31.976	2.402	0.116+	0.028	19.422	1.500
ϱ_{KKZ}	4.100	1.983	0.525	0.211	6.110	0.401
τ_{INV}	10.769	0.103	1.45E-15***	2.76E-15	0.515	0.034
ϱ_{SAU}	39.095	2.419	1.44E-3***	1.21E-3	10.546	0.792
ϱ_{SKZ}	-7.759	2.689	0.418	0.178	9.069	0.586
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.54 std. dev. 0.05, Eq. (2.21): mean 0.62 std. dev. 0.1, Eq. (2.26): mean 0.27 std. dev. 0.22, Eq. (2.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, + $p < 0.15$

Table A.3: Quadratic repr.: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	std. dev.	Mean	std. dev.	Mean	std. dev.
α_0	20.729	0.037	7.48E-35***	4.25E-34	0.105	7.40E-3
α_Q	2.27E-8	3.73E-9	1.52E-8***	3.73E-8	2.42E-9	2.61E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.89E-5	7.29E-50***	2.60E-50	1.11E-4	1.93E-6
α_E	1.894	0.130	9.09E-9***	2.04E-8	0.197	0.020
α_S	-0.214	0.149	0.197	0.275	0.116	0.041
γ_{KK}	-4.94E-4	1.89E-4	0.214	0.163	3.46E-4	3.97E-5
γ_{QQ}	2.78E-8	3.92E-9	4.98E-4***	4.51E-4	6.50E-9	6.49E-10
γ_{EE}	1.556	0.316	0.046**	0.090	0.616	0.096
$\gamma_{KQ} = -\gamma_{LQ}$	-8.33E-9	1.38E-9	0.043**	0.036	3.62E-9	4.06E-10
$\gamma_{KE} = -\gamma_{LE}$	2.10E-3	9.00E-5	1.70E-8***	9.03E-9	2.37E-4	1.13E-5
γ_{QE}	-2.66E-8	3.34E-9	5.85E-6***	4.45E-6	4.35E-9	5.27E-10
β_0	-7.353	4.180	0.109$^+$	0.227	2.718	0.390
β_1	0.099	0.149	0.577	0.292	0.158	0.023
β_2	0.048	8.32E-3	5.33E-4***	8.43E-4	0.011	1.32E-3
τ_{MFM}	37.310	15.355	0.271	0.157	30.708	2.457
τ_{CAP}	71.237	18.597	0.508	0.119	104.568	6.159
ϱ_{LAU}	13.218	1.714	0.042**	0.037	5.824	0.373
ϱ_{LKZ}	2.280	4.014	0.530	0.237	5.575	0.348
ϱ_{KAU}	37.954	3.371	0.011**	6.59E-3	13.294	1.016
ϱ_{KKZ}	8.187	1.531	0.092*	0.075	4.328	0.307
τ_{INV}	10.577	0.172	2.49E-16***	5.99E-16	0.433	0.028
ϱ_{SAU}	21.975	3.417	0.016**	0.047	7.459	0.517
ϱ_{SKZ}	-9.784	2.305	0.180	0.117	6.643	0.465
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.54 std. dev. 0.05, Eq. (2.21): mean 0.62 std. dev. 0.1, Eq. (2.26): mean 0.27 std. dev. 0.22, Eq. (2.28): mean 0.54 std. dev. 0.05					

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

Table A.4: Cubic repr.: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	std. dev.	Mean	std. dev.	Mean	std. dev.
α_0	20.722	0.036	1.58E-33***	8.58E-33	0.105	7.50E-3
α_Q	2.36E-8	4.19E-9	9.80E-8***	3.76E-7	2.68E-9	3.10E-10
$\alpha_K = 1 - \alpha_L$	0.102	2.00E-5	8.78E-48***	2.81E-48	1.10E-4	1.84E-6
α_E	1.910	0.129	1.30E-8***	2.78E-8	0.198	0.020
α_S	-0.215	0.149	0.189	0.271	0.116	0.041
γ_{KK}	-4.79E-4	1.85E-4	0.228	0.169	3.46E-4	3.97E-5
γ_{QQ}	2.79E-8	4.26E-9	1.37E-3***	1.05E-3	7.24E-9	8.20E-10
γ_{EE}	1.549	0.308	0.045**	0.082	0.616	0.096
$\gamma_{KQ} = -\gamma_{LQ}$	-8.05E-9	1.52E-9	0.072*	0.063	3.96E-9	5.42E-10
$\gamma_{KE} = -\gamma_{LE}$	2.13E-3	9.26E-5	2.53E-8***	1.36E-8	2.39E-4	1.16E-5
γ_{QE}	-2.80E-8	3.97E-9	1.14E-5***	8.09E-6	4.75E-9	7.02E-10
β_0	-6.516	4.643	0.126+	0.234	2.969	0.439
β_1	0.219	0.172	0.392	0.250	0.209	0.033
β_2	0.047	8.44E-3	4.30E-3***	6.84E-3	0.014	1.81E-3
β_3	-5.09E-4	2.71E-4	0.581	0.171	8.99E-4	1.09E-4
τ_{MFM}	38.888	15.631	0.265	0.133	31.737	2.967
τ_{CAP}	71.533	21.270	0.517	0.135	106.829	7.661
ϱ_{LAU}	14.204	1.694	0.048**	0.036	6.491	0.376
ϱ_{LKZ}	1.615	4.604	0.564	0.254	5.994	0.507
ϱ_{KAU}	36.335	3.637	0.020**	0.011	14.085	1.316
ϱ_{KKZ}	7.150	1.544	0.152	0.109	4.505	0.375
τ_{INV}	10.644	0.187	1.63E-15***	5.33E-15	0.440	0.034
ϱ_{SAU}	22.509	3.909	0.026**	0.080	8.187	0.561
ϱ_{SKZ}	-9.100	2.692	0.238	0.157	6.994	0.586
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.54 std. dev. 0.05, Eq. (2.21): mean 0.62 std. dev. 0.1, Eq. (2.26): mean 0.27 std. dev. 0.22, Eq. (2.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

Additional tables for the estimation results of Model 1

Table A.5: Estimation results for model without dynamic optimality condition: coefficients

Parameter	*Estimate*				
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	20.651	20.695	20.715	20.734	20.865
α_Q	1.26E-8	1.41E-8	1.57E-8	1.69E-8	2.13E-8
$\alpha_K = 1 - \alpha_L$	0.102	0.102	0.102	0.102	0.102
α_E	1.906	2.062	2.116	2.173	2.314
α_S	-0.512	-0.252	-0.204	-0.126	0.083
γ_{KK}	-1.07E-3	-6.04E-4	-4.72E-4	-3.49E-4	-1.26E-4
γ_{QQ}	1.00E-8	1.14E-8	1.34E-8	1.48E-8	2.09E-8
γ_{EE}	0.700	1.526	1.665	1.890	2.284
$\gamma_{KQ} = -\gamma_{LQ}$	-1.29E-8	-9.95E-9	-9.39E-9	-8.45E-9	-5.81E-9
$\gamma_{KE} = -\gamma_{LE}$	2.12E-3	2.31E-3	2.35E-3	2.39E-3	2.47E-3
γ_{QE}	-2.57E-8	-2.04E-8	-1.93E-8	-1.80E-8	-1.62E-8
β_0	-21.208	-19.674	-18.297	-17.390	-12.319
β_1	-0.171	-0.014	0.038	0.093	0.212
β_2	0.090	0.098	0.112	0.116	0.158
β_3	-1.34E-3	-1.07E-3	-8.98E-4	-7.60E-4	-2.79E-4
β_4	-2.87E-4	-1.92E-4	-1.84E-4	-1.56E-4	-1.37E-4
τ_{MFM}	-2.020	8.774	14.216	17.448	42.922
τ_{CAP}	49.882	84.249	93.717	103.215	127.432
ϱ_{LAU}	12.322	13.657	14.580	15.169	17.976
ϱ_{LKZ}	5.684	9.059	10.609	12.322	13.639
ϱ_{KAU}	19.332	23.716	25.376	26.697	33.292
ϱ_{KKZ}	5.916	8.167	8.555	9.143	9.918
τ_{INV}	10.490	10.642	10.713	10.771	10.968
ϱ_{SAU}	15.600	18.387	19.788	21.273	26.506
ϱ_{SKZ}	-9.671	-6.181	-4.434	-2.917	0.379
Observations	50×44				

Table A.6: Estimation results for model without dynamic optimality condition: coefficients

Parameter	*p-value*				
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	6.29E-34	2.91E-33	3.14E-32	1.08E-32	1.07E-30
α_Q	1.98E-6	1.58E-5	3.25E-5	4.46E-5	8.68E-5
$\alpha_K = 1 - \alpha_L$	4.72E-46	1.02E-45	1.36E-45	1.66E-45	2.41E-45
α_E	8.55E-10	2.54E-9	9.23E-9	9.64E-9	9.57E-8
α_S	1.36E-4	0.020	0.174	0.234	0.956
γ_{KK}	0.026	0.104	0.237	0.300	0.712
γ_{QQ}	0.020	0.065	0.104	0.142	0.248
γ_{EE}	7.03E-4	4.72E-3	0.031	0.023	0.326
$\gamma_{KQ} = -\gamma_{LQ}$	1.18E-3	8.75E-3	0.021	0.025	0.137
$\gamma_{KE} = -\gamma_{LE}$	9.33E-9	1.61E-8	2.89E-8	3.21E-8	1.55E-7
γ_{QE}	5.47E-5	2.38E-4	5.68E-4	7.31E-4	1.90E-3
β_0	8.94E-6	3.80E-5	7.66E-4	4.32E-4	0.013
β_1	0.365	0.626	0.741	0.907	0.994
β_2	5.35E-5	4.29E-4	1.11E-3	1.56E-3	5.05E-3
β_3	0.146	0.221	0.318	0.365	0.735
β_4	4.20E-4	4.05E-3	0.011	0.015	0.041
τ_{MFM}	0.150	0.530	0.617	0.727	0.933
τ_{CAP}	0.172	0.260	0.324	0.357	0.591
ϱ_{LAU}	7.60E-3	0.020	0.028	0.033	0.062
ϱ_{LKZ}	9.64E-3	0.022	0.076	0.112	0.330
ϱ_{KAU}	9.17E-3	0.032	0.049	0.049	0.144
ϱ_{KKZ}	0.012	0.025	0.041	0.046	0.134
τ_{INV}	1.84E-16	3.03E-16	3.66E-16	4.11E-16	6.38E-16
ϱ_{SAU}	3.37E-3	9.07E-3	0.016	0.020	0.040
ϱ_{SKZ}	0.136	0.341	0.513	0.666	0.999
Observations	50×44				

Table A.7: Estimation results for model without dynamic optimality condition: coefficients

Parameter	*Std. Error*				
	Min	25%-quantile	Mean	75%-quantile	Max
α_0	0.093	0.101	0.105	0.108	0.138
α_Q	2.54E-9	2.66E-9	2.82E-9	3.00E-9	3.30E-9
$\alpha_K = 1 - \alpha_L$	1.06E-4	1.10E-4	1.11E-4	1.13E-4	1.15E-4
α_E	0.184	0.200	0.211	0.218	0.261
α_S	0.060	0.085	0.116	0.132	0.259
γ_{KK}	2.83E-4	3.11E-4	3.49E-4	3.83E-4	4.44E-4
γ_{QQ}	6.72E-9	7.09E-9	7.58E-9	8.07E-9	8.94E-9
γ_{EE}	0.468	0.534	0.606	0.687	0.840
$\gamma_{KQ} = -\gamma_{LQ}$	3.04E-9	3.20E-9	3.47E-9	3.72E-9	4.30E-9
$\gamma_{KE} = -\gamma_{LE}$	2.43E-4	2.54E-4	2.59E-4	2.64E-4	2.72E-4
γ_{QE}	3.90E-9	4.18E-9	4.53E-9	4.89E-9	5.59E-9
β_0	3.533	3.687	3.910	4.129	4.536
β_1	0.183	0.192	0.209	0.225	0.258
β_2	0.024	0.026	0.028	0.030	0.034
β_3	7.56E-4	7.93E-4	8.45E-4	8.99E-4	1.02E-3
β_4	5.30E-5	5.63E-5	6.13E-5	6.60E-5	7.53E-5
τ_{MFM}	23.666	24.987	26.319	27.623	30.055
τ_{CAP}	84.385	87.785	91.125	94.147	101.531
ϱ_{LAU}	5.753	5.935	6.012	6.051	6.356
ϱ_{LKZ}	4.739	4.957	5.183	5.387	5.898
ϱ_{KAU}	10.394	11.055	11.694	12.230	13.659
ϱ_{KKZ}	3.481	3.639	3.809	3.948	4.356
τ_{INV}	0.410	0.415	0.419	0.422	0.431
ϱ_{SAU}	6.883	7.054	7.268	7.457	8.009
ϱ_{SKZ}	5.828	6.146	6.446	6.724	7.362
Observations	50×44				

A.2 Robustness Checks

Estimation without higher order transformations of exogenous variables as instrumental variables

As discussed in Section 2.4, our system of equations will be nonlinear in endogenous variables due to transformations of the endogenous variables (e.g., interactions with other variables and squaring). To address potential endogeneity issues, we follow Wooldridge

(2002) (Chapter 9.5) and use a set of squared and higher-order transformations of exogenous variables. To test our choice of variables, we estimate Model 1 and Model 2 with a reduced set of instrumental variables. Instead of using $\ln Q^3$, $\ln Q^4$, $\ln S^3$, $\ln S^4$, $\ln P^3$, $\ln P^4$, T, T^2, as well as the exogenous variables already used in our estimation equations, we use the exogenous variables already used in our estimation equations, as well as T, T^2. The estimation results are given in Tables A.8, A.9 and A.10.

Table A.8: Simplified instruments: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.620	0.045	9.78E-31***	3.10E-30	0.126	0.010
α_Q	2.58E-8	1.47E-9	2.47E-3***	7.55E-4	7.34E-9	1.71E-10
$\alpha_K = 1 - \alpha_L$	0.102	3.10E-6	1.26E-44***	6.00E-45	1.25E-4	3.14E-6
α_E	2.473	0.170	3.05E-7***	1.04E-6	0.291	0.031
α_S	-0.134	0.264	0.293	0.312	0.154	0.057
γ_{KK}	-2.41E-4	2.13E-4	0.588	0.245	4.26E-4	4.27E-5
γ_{QQ}	4.82E-8	2.44E-9	6.12E-3***	2.30E-3	1.55E-8	3.42E-10
γ_{EE}	2.667	0.688	0.043**	0.041	1.110	0.148
$\gamma_{KQ} = -\gamma_{LQ}$	-3.64E-8	1.40E-9	2.82E-4***	7.38E-5	8.17E-9	2.05E-10
$\gamma_{KE} = -\gamma_{LE}$	2.83E-3	9.84E-5	2.07E-7***	1.39E-7	3.55E-4	9.94E-6
γ_{QE}	-1.56E-8	1.12E-9	0.104+	0.026	9.05E-9	3.02E-10
β_0	-5.547	1.514	0.545	0.107	8.955	0.207
β_1	0.927	0.097	0.122+	0.028	0.567	0.020
β_2	0.131	0.019	0.017**	9.94E-3	0.047	1.61E-3
β_3	7.44E-3	3.74E-4	1.21E-3***	3.19E-4	1.95E-3	5.06E-5
β_4	1.00E-4	4.12E-5	0.352	0.181	1.02E-4	3.02E-6
τ_{MFM}	-44.119	13.153	0.570	0.118	75.759	3.626
τ_{CAP}	281.212	53.205	0.269	0.083	241.570	10.473
ϱ_{LAU}	19.536	1.396	0.135+	0.026	12.442	0.525
ϱ_{LKZ}	-31.898	3.518	0.044**	0.015	14.613	0.556
ϱ_{KAU}	106.437	8.349	0.038**	8.41E-3	47.374	1.901
ϱ_{KKZ}	-0.874	2.442	0.874	0.101	11.755	0.491
τ_{INV}	10.264	0.205	1.77E-10***	1.72E-10	0.822	0.039
ϱ_{SAU}	13.419	5.194	0.458	0.113	17.881	0.790
ϱ_{SKZ}	0.025	2.372	0.921	0.072	17.088	0.592
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.47 std. dev. 0.08, Eq. (2.21): mean 0.43 std. dev. 0.07, Eq. (2.26): mean 0.57 std. dev. 0.04, Eq. (2.28): mean 0.47 std. Dev. 0.08					

$^{***}\ p < 0.01, ^{**}\ p < 0.05, ^{*}\ p < 0.1, ^{+}\ p < 0.15$

Table A.9: Simplified instruments: Hausman test results for constant interest rates

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	1684.117	5006.961	0.018**	0.094
0.02	2438.72	10266.476	0.022**	0.128
0.03	2723.209	10845.397	0.054*	0.222
0.04	1553.409	4537.783	0.03**	0.167
0.05	721.678	2178.448	0.076*	0.253
0.06	1544.614	6129.165	0.041**	0.181
0.07	529.064	1133.182	0.057*	0.232
0.08	685.74	1673.32	0.057*	0.231
0.09	545.404	869.724	0.057*	0.23
0.1	571.335	893.317	0.026**	0.149
0.11	443.77	694.349	0.022**	0.12
0.12	429.996	623.075	0.035**	0.139
0.13	462.302	601.057	0.009***	0.047
0.14	386.714	481.56	0.041**	0.174
0.15	399.879	537.441	0.037**	0.161
0.16	444.773	802.049	0.033**	0.169
0.17	1208.095	4948.531	0.03**	0.169
0.18	519.925	1117.688	0***	0
0.19	431.879	617.551	0***	0
0.2	569.918	1132.179	0***	0
0.21	503.458	979.483	0***	0
0.22	816.422	2648.744	0***	0
0.23	689.117	1424.815	0***	0
0.24	1376.555	5656.499	0.008***	0.045
0.25	356.417	508.363	0.033**	0.138

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table A.10: Simplified instruments: Hausman test results for proportional variations of the actual canadian interest rate r

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	2806.53	9795.993	0.017^{**}	0.101
$r \cdot 0.5$	4210.452	123.101	0.032^{**}	0.147
$r \cdot 0.75$	1783.073	105.781	0.037^{**}	0.169
$r \cdot 1$	854.059	100.271	0.049^{**}	0.186
$r \cdot 1.25$	1135.411	96.706	0.04^{**}	0.178
$r \cdot 1.5$	537.023	98.237	0.029^{**}	0.167
$r \cdot 1.75$	524.807	99.078	0.028^{**}	0.166
$r \cdot 2$	502.346	104.862	0.027^{**}	0.156
$r \cdot 2.25$	479.99	96.347	0.021^{**}	0.125
$r \cdot 2.5$	425.095	96.835	0.042^{**}	0.175
$r \cdot 2.75$	399.722	98.238	0.013^{**}	0.053
$r \cdot 3$	373.576	104.687	0.033^{**}	0.169
$r \cdot 3.25$	420.606	108.966	0.038^{**}	0.173
$r \cdot 3.5$	868.896	105.875	0.002^{***}	0.01
$r \cdot 3.75$	507.577	131.428	0^{***}	0
$r \cdot 4$	443.043	109.229	0^{***}	0

$^{***}\ p < 0.01, ^{**}\ p < 0.05, ^{*}\ p < 0.1, ^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

As can be clearly seen from Tables A.9 and A.10 the results of the Hausman tests are robust. However, while we find that most coefficient estimates are robust, we find implausible results for ϱ_{LKZ}. A statistically significant negative estimate would mean that with increasing labor costs, as a supply shifter, would lead to lower prices. This however is economically implausible and hence, illustrates biased estimates and the importance of using higher order instruments.[36]

Estimation with dummy variables controlling for potential shocks

The observation period used within our estimation, includes two time periods that might have potential impact on the global uranium market. First, the global financial crisis of 2008 might have led to a demand reducing shocks. Second, the Fukushima nuclear disaster and the subsequent shut down of several nuclear power plants could have had an impact on market price setting. To test whether such effects are observable in the

[36]We find that out of the 2050 estimates of Model 2 (50 subsamples times 41 different interest rates) 631 face near singular matrices during estimation, exceeding the number of near singular matrices in our main model by far.

data, we replace the inverse residual demand function, as given in Equation (2.25), with the following equation:

$$P = \beta \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l + \sum_{i=1}^{3} \delta_i D_i. \tag{2.25$'$}$$

Equation (2.25′) includes three time dummy variables to capture the above mentioned potential shocks. The definition of the dummy variables is based on the findings of spikes in Figure 2.1. D_1 equals one for the third quarter of 2008 and zero for any other time step. D_2 equals one for the first quarter of 2012 and zero for any other time step. D_3 equals one for the second quarter of 2012 and zero for any other time step. The estimation results are given in Tables A.11, A.12 and A.13.

Table A.11: Shock dummy variables: Estimation results for model without dynamic optimality condition

Parameter	*Estimate*		*p-value*		*Std. Error*	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
α_0	20.710	0.034	6.11E-28***	2.26E-27	0.107	7.60E-3
α_Q	9.96E-9	2.11E-9	0.032**	0.104	3.65E-9	1.74E-10
$\alpha_K = 1 - \alpha_L$	0.102	1.30E-5	4.71E-39***	1.46E-39	1.14E-4	2.22E-6
α_E	2.141	0.102	7.02E-8***	7.51E-8	0.224	0.017
α_S	-0.188	0.144	0.238	0.256	0.119	0.041
γ_{KK}	-5.10E-4	2.00E-4	0.212	0.149	3.51E-4	4.28E-5
γ_{QQ}	4.72E-9	2.74E-9	0.643	0.137	1.03E-8	6.48E-10
γ_{EE}	1.683	0.299	0.031**	0.051	0.616	0.089
$\gamma_{KQ} = -\gamma_{LQ}$	-1.01E-8	8.82E-10	0.026**	9.66E-3	4.07E-9	2.95E-10
$\gamma_{KE} = -\gamma_{LE}$	2.36E-3	7.63E-5	2.53E-7***	1.41E-7	2.75E-4	7.96E-6
γ_{QE}	-9.62E-9	1.94E-9	0.178	0.099	6.59E-9	4.73E-10
β_0	-25.179	2.065	2.78E-4***	3.57E-4	5.116	0.262
β_1	-0.256	0.146	0.336	0.222	0.224	0.016
β_2	0.128	0.024	9.95E-3***	0.038	0.038	2.79E-3
β_3	-7.12E-5	4.44E-4	0.784	0.171	8.99E-4	5.35E-5
β_4	-2.26E-4	5.15E-5	0.036**	0.108	8.66E-5	6.41E-6
τ_{MFM}	-32.149	20.166	0.455	0.146	38.613	2.475
τ_{CAP}	114.394	42.163	0.448	0.140	140.722	4.889
ϱ_{LAU}	15.328	1.576	0.040**	0.013	6.753	0.279
ϱ_{LKZ}	10.536	2.609	0.146+	0.120	6.451	0.460
ϱ_{KAU}	24.879	5.490	0.249	0.146	20.145	0.838
ϱ_{KKZ}	13.239	1.112	0.017**	6.36E-3	4.944	0.371
τ_{INV}	10.490	0.152	1.44E-11***	9.75E-11	0.486	0.040
ϱ_{SAU}	18.266	2.181	0.054*	0.023	8.580	0.598
ϱ_{SKZ}	-0.295	2.846	0.853	0.153	8.592	0.448
δ_1	-7.866	4.733	0.454	0.133	10.942	1.023
δ_2	7.383	5.645	0.613	0.102	17.296	1.149
δ_3	-25.681	7.019	0.222	0.118	19.515	1.615
Observations	50×44					
Adjusted R^2	Eq. (2.18): mean 0.54 std. dev. 0.05, Eq. (2.21): mean 0.62 std. dev. 0.1, Eq. (2.26): mean 0.27 std. dev. 0.22, Eq. (2.28): mean 0.54 std. dev. 0.05					

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, $^{+}$ $p < 0.15$

Table A.12: Shock dummy variables: Hausman test results for constant interest rates

Interest rate	χ^2 *test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
0.01	737.217	1149.548	0.103^{+}	0.28
0.02	674.936	1181.231	0.067^{*}	0.234
0.03	810.951	1295.165	0.104^{+}	0.302
0.04	765.694	1271.562	0.104^{+}	0.239
0.05	951.724	2030.274	0.084^{*}	0.261
0.06	950.824	1549.972	0.067^{*}	0.241
0.07	1105.71	2070.77	0.094^{*}	0.282
0.08	813.206	1301.175	0.061^{*}	0.211
0.09	868.01	1303.886	0.044^{**}	0.187
0.1	940.62	1464.42	0.078^{*}	0.251
0.11	832.355	1211.427	0.06^{*}	0.223
0.12	937.656	1677.771	0.047^{**}	0.191
0.13	993.898	1716.678	0.064^{*}	0.241
0.14	782.812	1308.535	0.049^{**}	0.191
0.15	804.457	1407.83	0.05^{*}	0.189
0.16	5234.076	27117.246	0.083^{*}	0.271
0.17	763.876	1175.537	0.064^{*}	0.223
0.18	937.014	1621.986	0.05^{*}	0.211
0.19	704.424	1186.1	0.05^{*}	0.21
0.2	681.163	1157.198	0.077^{*}	0.258
0.21	776.816	1303.854	0.064^{*}	0.221
0.22	727.61	1183.675	0.074^{*}	0.249
0.23	671.346	1104.346	0.046^{**}	0.188
0.24	638.071	1084.896	0.051^{*}	0.186
0.25	755.862	1307.389	0.045^{**}	0.175

$^{***}\ p < 0.01, ^{**}\ p < 0.05, ^{*}\ p < 0.1, ^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Table A.13: Shock dummy variables: Hausman test results for proportional variations of the actual Canadian interest rate r

Interest rate	*χ^2 test statistic*		*p-value*	
	Mean	Std. Dev.	Mean	Std. Dev.
$r \cdot 0.25$	710.523	1143.932	0.072^{*}	0.216
$r \cdot 0.5$	655.868	56.58	0.065^{*}	0.205
$r \cdot 0.75$	1325.145	50.632	0.102^{+}	0.25
$r \cdot 1$	1217.06	64.829	0.047^{**}	0.19
$r \cdot 1.25$	924.326	135.989	0.067^{*}	0.242
$r \cdot 1.5$	863.447	102.821	0.064^{*}	0.235
$r \cdot 1.75$	864.167	100.167	0.049^{**}	0.196
$r \cdot 2$	1225.145	133.792	0.052^{*}	0.192
$r \cdot 2.25$	844.23	132.805	0.068^{*}	0.244
$r \cdot 2.5$	983.449	111.341	0.067^{*}	0.248
$r \cdot 2.75$	871.569	120.222	0.072^{*}	0.243
$r \cdot 3$	796.647	110.794	0.037^{**}	0.166
$r \cdot 3.25$	1068.129	127.346	0.081^{*}	0.264
$r \cdot 3.5$	804.02	127.107	0.103^{+}	0.266
$r \cdot 3.75$	777.663	120.227	0.05^{*}	0.211
$r \cdot 4$	703.321	123.534	0.051^{*}	0.21

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

The critical value (CV) for p=0.01 is at 37.566

Again, Tables A.12 and A.13 illustrate the results of the Hausman tests to be robust even under the alternative specification of the inverse residual demand curve. Further, we find all coefficient estimates to be robust. Noticeably, no dummy variable coefficient is statistically significant. Therefore, showing that shock effects on the world market should not be the factors explaining the negative Lerner index at these points in time.[37]

A.3 Data Appendix

Summary Statistics

Quantity of uranium extracted, E

Extraction volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from

[37]Out of the 2050 estimates of Model 2 (50 subsamples times 41 different interest rates) 723 models had near singularity issues during estimation, exceeding the number of near singular matrices in our main model by far.

Table A.14: Summary Statistics

Series	*Mean*	*Maximum*	*Minimum*	*Std. Dev.*	*Observations*
B	1.274332	4.070614	0.264269	1.029772	44
$\ln CR$	20.84144	22.94147	19.08893	1.150019	44
$\ln E$	0.022724	1.175044	-1.206911	0.460854	44
$\ln P$	3.333787	4.049799	2.470928	0.520859	44
$\ln Q$	-0.054477	0.807969	-1.11201	0.278829	44
$\ln S$	-0.042334	1.299977	-5.909206	0.665293	50×44
$\ln W_K$	0.00044	0.662086	-0.359989	0.223815	44
$\ln W_L$	0.00641	0.294694	-0.570092	0.203949	44
M_K	0.102294	0.103997	0.099066	0.001333	44
P	31.75191	57.38593	11.83343	14.49644	44
$\bar{r}$	0.033211	0.048234	0.012374	0.009906	44
T	0	21.5	-21.5	12.58251	44
$\ln V_{KAU}$	-0.041982	0.134903	-0.29417	0.13467	44
$\ln V_{KKZ}$	0.137492	0.61845	-0.446492	0.315771	44
$\ln V_{LAU}$	0.061223	0.502522	-0.432324	0.258745	44
$\ln V_{LKZ}$	-0.085882	0.288374	-0.742886	0.301522	44
$\ln V_{SAU}$	-0.044462	0.217286	-0.318706	0.222694	44
$\ln V_{SKZ}$	-0.049702	0.18477	-0.298063	0.124974	44
$\ln Y_{CAP}$	-0.003819	0.012031	-0.031199	0.00964	44
$\ln Y_{INV}$	2.98131	3.926857	2.093219	0.502895	44
$\ln Y_{MFM}$	0.001745	0.054552	-0.029454	0.027657	44

Cameco (2012b) and annual values from Cameco (2012a).

Quantity of final output, Q

Sales volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from Cameco (2012b) and annual values from Cameco (2012a).

Exploration expenditures, B

Exploration expenditures are given in Cameco (2012b). Quarterly expenditures are directly stated for the 4th quarter of the following years: 2008, 2009, 2010, 2011, 2012. Using information on annual exploration expenditures (Cameco, 2012a), quarterly values are calculated. In Cameco (2012b) and Cameco (2012a), monetary values are expressed in Canadian dollar. Real (2012) values are calculated using the U.S. Consumer price index (CPI) (U.S. Department of Labor, 2013) (converted to quarterly values by weighting by the number of days per month) and Canadian to U.S. dollar exchange rates. Exchange rates are expressed in Cameco (2012b). Missing data for the 4th quarter 2002 are substituted with data from Bank of Canada (2014a).

Additional exploration expenditure information for Canada used for estimating the exploration function, f, is taken from Nuclear Energy Agency (2006). Nominal values are converted to real (2012) values using Canadian Consumer Price Indices (OECD, 2013).

State of the technology, T

The state of the technology is expressed as a mean-adjusted linear trend.

Market price of final output, P

Data for the first three quarters of each year are taken from Cameco (2012b) using information on average realized prices. The market price for the final quarter of each year is calculated from annual data (Cameco, 2012b) weighted by sales volumes. Nominal values given in Canadian dollar are converted to real (2012) U.S. dollar using Canadian to U.S. dollar exchange rates (Bank of Canada, 2014a, Cameco, 2012b) and Canadian Consumer Price Indices (OECD, 2013).

Market price of reproducible input labor, W_L

The market price of reproducible input labor in Canada is based on two data sources. Average weekly wage rates for Saskatchewan for forestry, fishing, mining, quarrying, oil and gas (North American Industry Classification System) (Statistics Canada, 2013a) are converted using Canadian to U.S. dollar exchange rates (Bank of Canada, 2014a, Cameco, 2012b) and U.S. Consumer Price Indices (OECD, 2013). Supplementary benefits are received by calculating the share of supplementary benefits in monthly wages from Statistics Canada (2012) and scaling the converted average weekly wage rates accordingly.

Quantity of labor, X_L

Annual data for direct employment in uranium mining operations in Canada is taken from Nuclear Energy Agency (2011). Data for Cameco are obtained by scaling total numbers using ownership shares for mining operations and assuming an equal distribution of changes among seasons.

Market price of reproducible input capital, W_K

Following Ellis and Halvorsen (2002), we calculate the price of capital as the product of the producer price index (PPI, for the mining industry if available), the sum of the depreciation rate (assumed to be at 10%) and the real rate of interest. We derive market prices for capital for Canada using the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b) as well as real interest rates calculated from data for selected Canadian 10-year bond yields (Bank of Canada, 2014b) and Canadian consumer price indices (OECD, 2013).

Quantity of capital, X_K

Quantity of capital is derived via the perpetual inventory method. Year-end net value of property for the year 1996 as well as quarterly capital expenditures are taken from Cameco (2012a) and Cameco (2012b). Depreciation rates are assumed to be 10% and the producer price index is the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b). Exchange rates are from ABS (2014a) and X-RATES (2014).

Proven reserves, S

There are numerous classification schemes for uranium reserves and resources. We utilize definitions used by Nuclear Energy Agency (2011) and Cameco (2012a) and focus on proven reserves. Cameco (2012a) covers annual data for uranium reserves and resources. Quarterly values are imputed as described in Section 2.5.

Recycling of military warheads, Y_{MFM}

Annual data for the "Megatons to Megawatts" quantities are given by Centrus (2014). We assume an equal distribution of quantities among quarters.

Global thermal capacity of nuclear power plants, Y_{CAP}

Global thermal capacity of nuclear power plants are calculated from plant characteristics, and commissioning and decommissioning dates taken from International Atomic Energy Agency (2013).

Global inventories, Y_{INV}

Inventory data is, generally speaking, not publicly available. Nuclear Energy Agency (2011) includes graphical information on global uranium production and demand from 1945 (i.e., approximately ten years prior to the commissioning of the first nuclear reactor) up to 2011. The difference between total production and demand approximates global uranium inventories. Quarterly values are obtained from annual data from Nuclear Energy Agency (2011) using cubic splines.

Australian market prices for capital, V_{KAU}

Australian capital prices are obtained using PPI for the (coal) mining industry from ABS (2014d). Real (2012) rate of interest results from data for Commonwealth Government 10-year bonds (Reserve Bank of Australia, 2014) and inflation rates are calculated using ABS (2014c).

Kazakh market prices for capital, V_{KKZ}

Capital prices for Kazakhstan are based on the general PPI data from UNECE (2014). Using the Kazakh corporate bonds index KASE_BY (KASE, 2014b) and CPI data from UNECE (2014), real (2012) interest rates are calculated.

Australian market prices for labor, V_{LAU}

Data for Australian mining operations is taken from ABS (2014b). In order to convert the data to real (2012) U.S. dollar values, exchange rates from ABS (2014a) are used for January 2002 to March 2012. April 2012 to December 2012 are covered by X-RATES (2014). Both time series are weighted for quarterly values and adjusted using ABS (2014c).

Kazakh market prices for labor, V_{LKZ}

Kazakh mining industry monthly wage data for the years 2008 to 2012 is obtained from the Agency of Kazakhstan of Statistics (2014a). As sector-specific data is unavailable for years prior to 2008, we approximate mining wage data using changes in average wage statistics (Agency of Kazakhstan of Statistics, 2014c). Correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(-1.951)}{-1.128 \times 10^4} + \underset{(27.924)}{1.993} \text{ avg. wage.}$$

Assuming strong correlation between GDP and wage growth (Warner et al., 2006, e.g.) and further decreasing unemployment with growth in GDP, we approximate mining sector wage data for Kazakhstan using Kazakh labor statistics for changes in unemployment (Agency of Kazakhstan of Statistics, 2014b). Again, correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(32.64)}{4.901 \times 10^5} \underset{(-25.91)}{-671.36} \text{ unemployed population in thousands.}$$

Real (2012) values are obtained by conversion using KASE (2014a) and UNECE (2014).

Australian proven reserves, V_{SAU}

Australian annual data is taken from Australia (2013). Quarterly values are assumed to be identical to annual values.

Kazakh proven reserves, V_{SKZ}

Rempel et al. (2013) include annual data on Kazakh uranium reserves. Quarterly values are assumed to be identical to annual values.

Canadian interest rate, $\tilde{r}$

See *Market price of reproducible input capital*.

Appendix B

Supplementary Material for Chapter 3

B.1 The open-loop model

B.1.1 Solving the general open-loop Cournot model

Proof of Theorem 3.1. The problem can be rewritten as a variational inequality (VI). For this define

$$
\begin{aligned}
&x_j^t = (x_{1,j}^t, x_{2,j}^t), G_{i,j}^t(x_j^t) = \delta_{i,j} - [a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t)] + b \cdot x_{i,j}^t \\
&x^t = (x_1^t, x_2^t), G_i^t(x^t) = (G_{i,1}^t(x_1^t), G_{i,2}^t(x_2^t)) \\
&G^t(x^t) = (G_1^t(x^t), G_2^t(x^t)) \\
&x = (x^1, ..., x^T), G(x) = (G^1(x^1), ..., G^T(x^T)) \\
&y = (y_1, y_2), k = (k_1, k_2), F(y, x) = (k, G(x)).
\end{aligned}
$$

and let Z denote the set of feasible (y, x).
$G(x)$ is strictly monotone, as

$$
\begin{aligned}
& [G^t(x^{t,1}) - G^t(x^{t,2})](x^{t,1} - x^{t,2})^\intercal \\
= \quad & \sum_j b(x_{1,j}^{t,1} - x_{1,j}^{t,2}, x_{2,j}^{t,1} - x_{2,j}^{t,2}) \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix} (x_{1,j}^{t,1} - x_{1,j}^{t,2}, x_{2,j}^{t,1} - x_{2,j}^{t,2})^\intercal > 0
\end{aligned}
$$

for $x^{t,1} \neq x^{t,2}$. Similarly, $F(y, x)$ is monotone, as

$$
\begin{aligned}
& [F(y^1, x^1) - F(y^2, x^2)] \begin{pmatrix} y^1 - y^2 \\ x^1 - x^2 \end{pmatrix} \\
= \quad & (0, 0, G(y^1, x^1) - G(y^2, x^2)) \begin{pmatrix} y_1^1 - y_1^2 \\ y_2^1 - y_2^2 \\ x^1 - x^2 \end{pmatrix} \\
= \quad & (G(y^1, x^1) - G(y^2, x^2))(x^1 - x^2) \geq 0
\end{aligned}
$$

and > 0 when $x^1 \neq x^2$.
The open-loop problem can now be stated in terms of a VI as follows:
Find (y^*, x^*) with $cap_i^0 + y_i^* - \sum_j x_{i,j}^{t*} \geq 0, x_{i,j}^{t*} \geq 0$ satisfying

$$F(y^*, x^*)(y - y^*, x - x^*)^\intercal \geq 0$$

for all (y, x) with $cap_i^0 + y_i - \sum_j x_{i,j}^t \geq 0, x_{i,j}^t \geq 0$.
As $0 \leq x_{i,j}^t \leq \frac{a_j^t}{b}$ and $y_i \leq 2 \max \frac{a_j^t}{b}$, the VI is defined over a convex and bounded set. From this together with the continuity of F, existence follows from the general theory

on VIs. Uniqueness in x is guaranteed by the monotonicity of $G(x)$ and uniqueness in y follows since $y_i = \max_t \left(\sum_j x^t_{i,j} - cap^0_i \right)$. □

B.1.2 Solving the one-period open-loop Cournot model with no given capacities to the players

In the one-period open-loop Cournot model with no given capacities available to the players, the short-term KKT conditions simplify to

$$
\begin{aligned}
&0 \leq \delta_{i,j} - [a_j - b \cdot (x_{i,j} + x_{-i,j})] + b \cdot x_{i,j} + \lambda_i \perp x_{i,j} \geq 0, \ \forall i, j \\
&0 \leq y_i - \sum_j x_{i,j} \perp \lambda_i \geq 0, \ \forall i.
\end{aligned}
$$

The long-term KKT conditions are given by

$$0 \leq k_i - \lambda_i \perp y_i \geq 0, \ \forall i.$$

From the long-term KKT condition it follows that in the one-period case all capacity is fully utilized. Closed-form solutions are obtained by distinguishing the following cases, leaving aside symmetric cases:

- Both players produce and supply both markets, i.e., $x_{ij} > 0$ for all i, j:
  When solving the resulting system of equations, it follows

$$x_{i,j} = \frac{a_j + \delta_{-i,j} - 2\delta_{i,j} + k_{-i} - 2k_i}{3b}.$$

- Player 1 supplies both markets, player 2 only market 1, i.e., $x_{1,1} > 0$, $x_{1,2} > 0$, $x_{2,1} > 0$ and $x_{2,2} = 0$:
  When solving the resulting system of equations, it follows

$$
\begin{aligned}
x_{1,2} &= \frac{a_2 - \delta_{1,2} - k_1}{2b} \text{ and } x_{2,2} = 0, \\
x_{i,1} &= \frac{a_1 + \delta_{-i,1} - 2\delta_{i,1} + k_{-i} - 2k_i}{3b}.
\end{aligned}
$$

- Player 1 supplies both markets, player 2 none, i.e., $x_{1,1} > 0$, $x_{1,2} > 0$, $x_{2,1} = 0$ and $x_{2,2} = 0$:
  When solving the resulting system of equations, it follows

$$
\begin{aligned}
x_{1,j} &= \frac{a_j - \delta_{1,j} - k_1}{2b}, \\
x_{2,j} &= 0.
\end{aligned}
$$

- Player 1 supplies market 1, player 2 supplies market 2, i.e., $x_{1,1} > 0$, $x_{1,2} = 0$, $x_{2,1} = 0$ and $x_{2,2} > 0$:
  When solving the resulting system of equations, it follows

$$\begin{aligned} x_{1,1} &= \frac{a_1 - \delta_{1,1} - k_1}{2b} \text{ and } x_{1,2} = 0, \\ x_{2,2} &= \frac{a_2 - \delta_{2,2} - k_2}{2b} \text{ and } x_{2,1} = 0. \end{aligned}$$

- Player 1 supplies market 1, player 2 none, i.e., $x_{1,1} > 0$, $x_{1,2} = 0$, $x_{2,1} = 0$ and $x_{2,2} = 0$:
  When solving the resulting system of equations, it follows

$$\begin{aligned} x_{1,1} &= \frac{a_1 - \delta_{1,1} - k_1}{2b} \text{ and } x_{1,2} = 0, \\ x_{2,j} &= 0. \end{aligned}$$

- No player supplies, i.e., $x_{i,j} = 0$ for all i, j.

B.1.3 Solving the multi-period open-loop Cournot model

In the multi-period open-loop Cournot model with no existing capacity available to the players, time points in which the capacity constraint is binding, termed TB, have to be distinguished from those in which it is not binding. Any solution to the optimization problem then satisfies the short-term Karush-Kuhn-Tucker (KKT) conditions

$$\begin{aligned} &0 \leq \delta_{i,j} - [a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t)] + b \cdot x_{i,j}^t + \lambda_i^t \perp x_{i,j}^t \geq 0, \ \forall i, j, t \in TB \\ &0 \leq \delta_{i,j} - [a_j^t - b \cdot (x_{i,j}^t + x_{-i,j}^t)] + b \cdot x_{i,j}^t \perp x_{i,j}^t \geq 0, \ \forall i, j, t \notin TB \\ &0 = y_i - \sum_j x_{i,j}^t, \ \forall i, t \in TB \\ &0 \leq y_i - \sum_j x_{i,j}^t \perp \lambda_i^t \geq 0, \ \forall i, t \notin TB \end{aligned}$$

as well as the long-term KKT conditions

$$0 \leq k_i - \sum_{t \in TB} \lambda_i^t \perp y_i \geq 0, \ \forall i.$$

Again, it is possible to obtain closed-form solutions for the multi-period open-loop Cournot model using similar case analysis as for the one-period model. See Wogrin et al. (2013b) for additional technicalities of this procedure.

B.2 Comparing the open-loop and closed-loop Cournot model

Proof of Lemma 3.2. The $x^t_{i,j}(y)$ are unique for all y as for a given investment vector y the second stage problem is just a series of spatial, single stage Cournot games. The $x^t_{i,j}(y)$ are continuous in y from which right and left-differentiability in the components follows. □

Proof of Lemma 3.4. The claim follows by taking derivatives in the following cases:

1. Both players produce and supply both markets, i.e., $x^t_{i,j} > 0$ for all i, j

(1a) Both players produce at full capacity, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0 : \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} + \lambda^t_1 = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + b \cdot x^t_{2,2} + \lambda^t_1 = 0 \\
0 < x^t_{2,1} + x^t_{2,2} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0 : \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} + \lambda^t_2 = 0 \\
& \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + b \cdot x^t_{1,2} + \lambda^t_2 = 0
\end{aligned}$$

(1b) Both players do not produce at full capacity, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0 : \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + b \cdot x^t_{2,2} = 0 \\
0 < x^t_{2,1} + x^t_{2,2} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0 : \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} = 0 \\
& \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + b \cdot x^t_{1,2} = 0
\end{aligned}$$

(1c) Player 1 produces at full capacity, player 2 does not, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0 : \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} + \lambda^t_1 = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + b \cdot x^t_{2,2} + \lambda^t_1 = 0 \\
0 < x^t_{2,1} + x^t_{2,2} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0 : \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} = 0 \\
& \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + b \cdot x^t_{1,2} = 0
\end{aligned}$$

(1d) Player 1 does not produce at full capacity, player 2 does, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + b \cdot x^t_{2,2} = 0 \\
0 < x^t_{2,1} + x^t_{2,2} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} + \lambda^t_2 = 0 \\
& \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + b \cdot x^t_{1,2} + \lambda^t_2 = 0
\end{aligned}$$

2. Player 1 supplies both markets, player 2 only market 1, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} > 0$, $x^t_{2,1} > 0$ and $x^t_{2,2} = 0$

(2a) Both players produce at full capacity, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \quad \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} + \lambda^t_1 = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + \lambda^t_1 = 0 \\
0 < x^t_{2,1} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} + \lambda^t_2 = 0 \\
& \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} + \lambda^t_2 \geq 0
\end{aligned}$$

(2b) Both players do not produce at full capacity, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} = 0 \\
0 < x^t_{2,1} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} = 0 \\
& \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} \geq 0
\end{aligned}$$

(2c) Player 1 produces at full capacity, player 2 does not, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} + \lambda^t_1 = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + \lambda^t_1 = 0 \\
0 < x^t_{2,1} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} = 0 \\
& \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} \geq 0
\end{aligned}$$

(2d) Player 1 does not produce at full capacity, player 2 does, i.e.,

$$\begin{aligned}
0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + b \cdot x^t_{2,1} = 0 \\
& \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} = 0 \\
0 < x^t_{2,1} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + 2b \cdot x^t_{2,1} + b \cdot x^t_{1,1} + \lambda^t_2 = 0 \\
& \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} + \lambda^t_2 \geq 0
\end{aligned}$$

3. Player 1 supplies both markets, player 2 none, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} > 0$, $x^t_{2,1} = 0$ and $x^t_{2,2} = 0$

   (3a) Player 1 produces at full capacity, player 2 does at zero, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + \lambda^t_1 = 0 \\ & \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + \lambda^t_1 = 0 \\ 0 = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} + \lambda^t_2 \geq 0 \\ & \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} + \lambda^t_2 \geq 0 \end{aligned}$$

   (3b) Both players do not produce at full capacity, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} = 0 \\ & \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} = 0 \\ 0 < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} \geq 0 \\ & \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} \geq 0 \end{aligned}$$

   (3c) Player 1 produces at full capacity, player 2 does not, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} + x^t_{1,2} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + \lambda^t_1 = 0 \\ & \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} + \lambda^t_1 = 0 \\ 0 < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} \geq 0 \\ & \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} \geq 0 \end{aligned}$$

   (3d) Player 1 does not produce at full capacity, player 2 does at zero, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} + x^t_{1,2} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} = 0 \\ & \delta^t_{1,2} - a^t_2 + 2b \cdot x^t_{1,2} = 0 \\ 0 = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} + \lambda^t_2 \geq 0 \\ & \delta^t_{2,2} - a^t_2 + b \cdot x^t_{1,2} + \lambda^t_2 \geq 0 \end{aligned}$$

4. Player 1 supplies market 1, player 2 supplies market 2, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} = 0$, $x^t_{2,1} = 0$ and $x^t_{2,2} > 0$

(4a) Both players produce at full capacity, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + \lambda^t_1 = 0 \\ & \delta^t_{1,2} - a^t_2 + b \cdot x^t_{2,2} + \lambda^t_1 \geq 0 \\ 0 < x^t_{2,2} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} + \lambda^t_2 \geq 0 \\ & \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + \lambda^t_2 = 0 \end{aligned}$$

(4b) Both players do not produce at full capacity, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} = 0 \\ & \delta^t_{1,2} - a^t_2 + b \cdot x^t_{2,2} \geq 0 \\ 0 < x^t_{2,2} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} \geq 0 \\ & \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} = 0 \end{aligned}$$

(4c) Player 1 produces at full capacity, player 2 does not, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + \lambda^t_1 = 0 \\ & \delta^t_{1,2} - a^t_2 + b \cdot x^t_{2,2} + \lambda^t_1 \geq 0 \\ 0 < x^t_{2,2} < cap^0_2 + y_2 \Rightarrow \lambda^t_2 = 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} \geq 0 \\ & \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} = 0 \end{aligned}$$

(4d) Player 1 does not produce at full capacity, player 2 does, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} < cap^0_1 + y_1 \Rightarrow \lambda^t_1 = 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} = 0 \\ & \delta^t_{1,2} - a^t_2 + b \cdot x^t_{2,2} \geq 0 \\ 0 < x^t_{2,2} = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} + \lambda^t_2 \geq 0 \\ & \delta^t_{2,2} - a^t_2 + 2b \cdot x^t_{2,2} + \lambda^t_2 = 0 \end{aligned}$$

5. Player 1 supplies market 1, player 2 does not supply, i.e., $x^t_{1,1} > 0$, $x^t_{1,2} = 0$, $x^t_{2,1} = 0$ and $x^t_{2,2} = 0$

(5a) Both players produce at full capacity, i.e.,

$$\begin{aligned} 0 < x^t_{1,1} = cap^0_1 + y_1 \text{ and } \lambda^t_1 \geq 0: \quad & \delta^t_{1,1} - a^t_1 + 2b \cdot x^t_{1,1} + \lambda^t_1 = 0 \\ & \delta^t_{1,2} - a^t_2 + \lambda^t_1 \geq 0 \\ 0 = cap^0_2 + y_2 \text{ and } \lambda^t_2 \geq 0: \quad & \delta^t_{2,1} - a^t_1 + b \cdot x^t_{1,1} + \lambda^t_2 \geq 0 \\ & \delta^t_{2,2} - a^t_2 + \lambda^t_2 \geq 0 \end{aligned}$$

(5b) Both players do not produce at full capacity, i.e.,

$$
\begin{aligned}
0 < x_{1,1}^t < cap_1^0 + y_1 \Rightarrow \lambda_1^t = 0: \quad & \delta_{1,1}^t - a_1^t + 2b \cdot x_{1,1}^t = 0 \\
& \delta_{1,2}^t - a_2^t \geq 0 \\
0 < cap_2^0 + y_2 \Rightarrow \lambda_2^t = 0: \quad & \delta_{2,1}^t - a_1^t + b \cdot x_{1,1}^t \geq 0 \\
& \delta_{2,2}^t - a_2^t \geq 0
\end{aligned}
$$

(5c) Player 1 produces at full capacity, player 2 does not, i.e.,

$$
\begin{aligned}
0 < x_{1,1}^t = cap_1^0 + y_1 \text{ and } \lambda_1^t \geq 0: \quad & \delta_{1,1}^t - a_1^t + 2b \cdot x_{1,1}^t + \lambda_1^t = 0 \\
& \delta_{1,2}^t - a_2^t + \lambda_1^t \geq 0 \\
0 < cap_2^0 + y_2 \Rightarrow \lambda_2^t = 0: \quad & \delta_{2,1}^t - a_1^t + b \cdot x_{1,1}^t \geq 0 \\
& \delta_{2,2}^t - a_2^t \geq 0
\end{aligned}
$$

(5d) Player 1 does not produce at full capacity, player 2 does, i.e.,

$$
\begin{aligned}
0 < x_{1,1}^t < cap_1^0 + y_1 \Rightarrow \lambda_1^t = 0: \quad & \delta_{1,1}^t - a_1^t + 2b \cdot x_{1,1}^t = 0 \\
& \delta_{1,2}^t - a_2^t \geq 0 \\
0 = cap_2^0 + y_2 \text{ and } \lambda_2^t \geq 0: \quad & \delta_{2,1}^t - a_1^t + b \cdot x_{1,1}^t + \lambda_2^t \geq 0 \\
& \delta_{2,2}^t - a_2^t + \lambda_2^t \geq 0
\end{aligned}
$$

□

Appendix C

Supplementary Material for Chapter 4

C.1 Data Appendix

Table C.1: Distance

from	to	distance [Nautical miles]
United States	Europe-Atlantic	3,387
	Asia-Pacific	10,978
Australia	Europe-Atlantic	11,626
	Asia-Pacific	3,731
Canada	Europe-Atlantic	8,840
	Asia-Pacific	4,227
Fringe	Europe-Atlantic	5,018
	Asia-Pacific	3,037

Table C.2: Reference Demand and Reference Price

Market	Reference Demand [Mt]	Reference Price [US$/t]
Europe-Atlantic	96	180
Asia-Pacific	179	180

C.2 An analytical example

We provide an intuition for the results presented in this paper by solving analytically a simplified model consisting of one market and two players. Player I is the incumbent in the market and has infinite existing capacity. Player E is the entrant to the market owning no existing capacity. The entrant can invest at cost k per unit, whereas the incumbent may not invest. Both players produce at variable production costs c and there are no transportation costs to the market. There is only one time period and the inverse residual demand curve for this period is given by $P = a - (x_I + x_E)$.

We solve both the open-loop and the closed-loop model for this simplified setting and show that there is an incentive for the players in the closed-loop model to deviate from their open-loop equilibrium quantities.[38]

[38]We restrict our attention to parameter settings in which both players produce. This restriction is adequate for the objective at hand, namely to provide intuition for the main results in the paper.

The open-loop model

In the open-loop model, the entrant's optimization problem is given by

$$\max_{x_E, y_E} P \cdot x_E - c \cdot x_E - k \cdot y_E$$

subject to

$$\begin{aligned} &y_E - x_E \geq 0 \ (\lambda_E), \\ &x_E \geq 0, \\ &y_E \geq 0. \end{aligned}$$

From the corresponding KKT conditions, it is easy to see that in an open-loop equilibrium the capacity of the entrant is fully utilized, i.e., $y_E = x_E$. Therefore the optimization problem may be simplified to

$$\max_{x_E \geq 0} P \cdot x_E - (c + k) \cdot x_E.$$

Taking the derivative with respect to x_E, we obtain the first order condition

$$a - 2x_E - x_I - (c + k) = 0$$

from which we obtain the entrant's reaction curve

$$x_E = \frac{a - (c + k) - x_I}{2}.$$

The incumbent faces a different optimization problem, as he may not invest but has infinite existing capacity. The incumbent's optimization problem is hence given by

$$\max_{x_I \geq 0} P \cdot x_I - c \cdot x_I$$

which yields, when taking the derivative with respect to x_I, the first order condition

$$a - 2x_I - x_E - c = 0.$$

The first order condition can be solved for x_I to obtain the incumbent's reaction curve

$$x_I = \frac{a - c - x_E}{2}.$$

Solving the system of equations consisting of the two reaction curves for the players' supply quantities, we obtain

$$x_I = \frac{a - c + k}{3}$$

and

$$x_E = \frac{a - c - 2k}{3},$$

which is the solution to the open-loop model if the non-negativity conditions for x_I and x_E are fulfilled.

The closed-loop model

In order to solve the closed-loop model we use backward induction. For this let y_E denote the first stage investment volume of the entrant. The entrant's second stage optimization problem is then given by

$$\max_{x_E \geq 0} P \cdot x_E - c \cdot x_E$$

subject to

$$y_E - x_E \geq 0 \ (\lambda_E).$$

The Lagrangian to this optimization problem is given by

$$\mathcal{L} = P \cdot x_E - c \cdot x_E + \lambda_E \cdot (y_E - x_E)$$

from which the KKT conditions follow:

$$x_E = \frac{a - (c + \lambda_E) - x_I}{2},$$
$$0 \leq \lambda_E \perp y_E - x_E \geq 0.$$

The incumbent faces the optimization problem

$$\max_{x_I \geq 0} P \cdot x_I - c \cdot x_I$$

which yields, as in the open-loop model, the reaction curve

$$x_I = \frac{a - c - x_E}{2}.$$

By inserting this in the above KKT condition we obtain the expression

$$x_E = \frac{a - c - 2\lambda_E}{3}.$$

The first stage optimization problem of the entrant is then given by

$$\max_{y_E \geq 0} P \cdot x_E - c \cdot x_E - k \cdot y_E$$

subject to

$$\begin{aligned} x_E &= \frac{a-c-2\lambda_E}{3} \\ 0 &\leq \lambda_E \perp y_E - x_E \geq 0, \\ x_I &= \frac{a-c-x_E}{2}. \end{aligned}$$

Consider the case in which the capacity of the entrant is fully utilized, i.e., $x_E = y_E$. In this case the optimization problem may be simplified to

$$\max_{y_E \geq 0} P \cdot y_E - (c+k) \cdot y_E$$

subject to

$$\begin{aligned} \frac{a-c}{3} - y_E &\geq 0 \; (\mu_E), \\ x_I &= \frac{a-c-y_E}{2}. \end{aligned}$$

The Lagrangian to this optimization problem is given by

$$\mathcal{L} = \left[a - \left(y_E + \frac{a-c-y_E}{2}\right)\right] \cdot y_E - (c+k) \cdot y_E + \mu_E \cdot \left(\frac{a-c}{3} - y_E\right)$$

from which the KKT conditions follow:

$$\begin{aligned} y_E &= \frac{a-c-2k-2\mu_E}{2}, \\ 0 \leq \mu_E &\perp \frac{a-c}{3} - y_E \geq 0. \end{aligned}$$

In case of $\mu_E > 0$, we obtain

$$y_E = x_E = x_I = \frac{a-c}{3}$$

and $\lambda_E = 0$.[39]

This is indeed a solution in case

$$\mu_E = \frac{a-c-2k-2y_E}{2} = \frac{a-c}{6} - k > 0.$$

[39]This is also the limiting case for $x_E < y_E$.

In case of $\mu_E = 0$, we obtain

$$y_E = x_E = \frac{a - c - 2k}{2}$$

and

$$x_I = \frac{a - c + 2k}{4}.$$

which is a solution if

$$\lambda_E = \frac{a - c - 3y_E}{2} \geq 0$$

and

$$y_E \leq \frac{a - c}{3}.$$

Conclusion

These simple calculations show that the investment in the closed-loop model is higher than in the open-loop model for the entrant as

$$\frac{a - c - 2k}{2} \geq \frac{a - c - 2k}{3}$$

and

$$\frac{a - c}{3} \geq \frac{a - c - 2k}{3}.$$

We conclude that there is an incentive for the players in the closed-loop game to deviate from the open-loop equilibrium. Further investigation of the above considered cases also shows that the total supply is higher and prices are lower in the closed-loop model than in the open-loop model.

Appendix D

Supplementary Material for Chapter 5

D.1 Data Appendix

Table D.1: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y prolongation

State	Probability	Region	Invest Costs	Fixed O&M Costs	Var. Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
S1	low	Fr	0.2	-0.1	-1.3	1.1	-0.2
S1	low	EU excl. Fr	0.2	-0.1	1.2	-1.1	0.2
S1	low	EU incl. Fr	0.4	-0.2	-0.2	0.0	0.1
S1	medium	Fr	0.2	-0.1	-1.4	1.2	-0.1
S1	medium	EU excl. Fr	0.2	-0.1	1.3	-1.2	0.2
S1	medium	EU incl. Fr	0.4	-0.2	-0.1	0.0	0.1
S1	high	Fr	0.1	-0.1	-1.1	0.9	-0.1
S1	high	EU excl. Fr	0.2	-0.1	0.9	-0.9	0.2
S1	high	EU incl. Fr	0.3	-0.1	-0.1	0.0	0.0
S2	low	Fr	-1.0	-0.4	0.7	1.2	0.5
S2	low	EU excl. Fr	0.1	-0.2	1.4	-1.3	0.0
S2	low	EU incl. Fr	-1.0	-0.6	2.1	0.0	0.5
S2	medium	Fr	-0.7	-0.3	0.5	0.8	0.3
S2	medium	EU excl. Fr	0.0	-0.1	1.0	-0.8	0.0
S2	medium	EU incl. Fr	-0.7	-0.4	1.5	0.0	0.3
S2	high	Fr	-0.4	-0.1	0.4	0.3	0.1
S2	high	EU excl. Fr	0.0	-0.1	0.4	-0.3	0.0
S2	high	EU incl. Fr	-0.4	-0.2	0.8	0.0	0.2
S3	low	Fr	-1.0	-0.5	0.1	1.6	0.2
S3	low	EU excl. Fr	0.1	0.0	1.7	-1.6	0.2
S3	low	EU incl. Fr	-0.9	-0.5	1.8	0.0	0.4
S3	medium	Fr	-0.6	-0.3	0.0	1.1	0.1
S3	medium	EU excl. Fr	-0.1	0.0	1.3	-1.1	0.2
S3	medium	EU incl. Fr	-0.7	-0.4	1.4	0.0	0.3
S3	high	Fr	-0.4	-0.2	0.2	0.5	0.1
S3	high	EU excl. Fr	0.0	0.0	0.5	-0.4	0.0
S3	high	EU incl. Fr	-0.4	-0.2	0.8	0.0	0.2
S4	low	Fr	0.0	0.0	0.0	0.0	0.0
S4	low	EU excl. Fr	0.1	0.0	-0.1	0.0	0.0
S4	low	EU incl. Fr	0.1	0.0	-0.1	0.0	0.0
S4	medium	Fr	0.3	0.2	-0.1	-0.3	0.1
S4	medium	EU excl. Fr	0.0	0.0	-0.4	0.3	-0.1
S4	medium	EU incl. Fr	0.3	0.2	-0.5	0.0	0.0
S4	high	Fr	0.5	0.4	0.1	-0.8	0.2
S4	high	EU excl. Fr	0.0	0.0	-1.1	0.8	-0.2
S4	high	EU incl. Fr	0.6	0.4	-1.0	0.0	0.0
S5	low	Fr	0.0	0.0	0.0	0.0	0.0
S5	low	EU excl. Fr	0.1	0.0	-0.1	0.0	0.0
S5	low	EU incl. Fr	0.1	0.0	-0.1	0.0	0.0
S5	medium	Fr	0.3	0.2	-0.1	-0.3	0.1
S5	medium	EU excl. Fr	-0.1	0.0	-0.4	0.3	-0.1
S5	medium	EU incl. Fr	0.2	0.2	-0.5	0.0	0.0
S5	high	Fr	0.5	0.4	0.1	-0.8	0.2
S5	high	EU excl. Fr	0.0	0.0	-1.1	0.8	-0.2
S5	high	EU incl. Fr	0.6	0.4	-1.0	0.0	0.0

Table D.2: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y prolongation

State	Prob-ability	Region	Invest Costs	Fixed O&M Costs	Var. Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
S1	low	Fr	0.4	-0.2	0.2	-0.3	0.1
S1	low	EU excl. Fr	0.3	-0.2	0.0	0.2	0.3
S1	low	EU incl. Fr	0.6	-0.4	0.1	0.0	0.4
S1	medium	Fr	0.2	-0.2	0.4	-0.3	0.1
S1	medium	EU excl. Fr	0.2	-0.2	-0.1	0.2	0.2
S1	medium	EU incl. Fr	0.4	-0.4	0.3	0.0	0.3
S1	high	Fr	0.0	0.0	0.6	-0.7	-0.1
S1	high	EU excl. Fr	0.1	-0.2	-0.4	0.7	0.1
S1	high	EU incl. Fr	0.1	-0.2	0.2	0.0	0.1
S2	low	Fr	1.8	0.4	-1.0	-1.0	0.2
S2	low	EU excl. Fr	-0.2	-0.1	-0.5	0.9	0.1
S2	low	EU incl. Fr	1.6	0.3	-1.5	0.0	0.3
S2	medium	Fr	1.5	0.3	-0.8	-0.9	0.2
S2	medium	EU excl. Fr	-0.2	-0.1	-0.5	0.8	0.0
S2	medium	EU incl. Fr	1.2	0.3	-1.3	0.0	0.2
S2	high	Fr	1.4	0.4	-0.5	-1.1	0.3
S2	high	EU excl. Fr	-0.2	-0.1	-0.8	1.1	0.0
S2	high	EU incl. Fr	1.2	0.3	-1.3	0.0	0.2
S3	low	Fr	1.8	0.6	0.7	-2.5	0.6
S3	low	EU excl. Fr	-1.2	-0.3	-1.1	2.5	-0.1
S3	low	EU incl. Fr	0.6	0.3	-0.3	0.0	0.5
S3	medium	Fr	1.5	0.4	0.8	-2.1	0.6
S3	medium	EU excl. Fr	-0.9	-0.3	-1.1	2.1	-0.2
S3	medium	EU incl. Fr	0.5	0.2	-0.2	0.0	0.4
S3	high	Fr	1.3	0.4	1.1	-2.1	0.7
S3	high	EU excl. Fr	-0.7	-0.2	-1.5	2.1	-0.2
S3	high	EU incl. Fr	0.6	0.3	-0.4	0.0	0.4
S4	low	Fr	0.6	0.2	0.5	-1.0	0.3
S4	low	EU excl. Fr	-0.4	-0.1	-0.5	1.0	-0.1
S4	low	EU incl. Fr	0.2	0.1	0.0	0.0	0.3
S4	medium	Fr	0.4	0.0	0.8	-0.8	0.4
S4	medium	EU excl. Fr	-0.3	-0.1	-0.6	0.8	-0.1
S4	medium	EU incl. Fr	0.1	0.0	0.1	0.0	0.3
S4	high	Fr	0.4	0.1	1.2	-1.1	0.6
S4	high	EU excl. Fr	0.0	0.0	-1.4	1.1	-0.3
S4	high	EU incl. Fr	0.3	0.1	-0.2	0.0	0.3
S5	low	Fr	-0.3	-0.2	0.4	0.1	0.1
S5	low	EU excl. Fr	0.1	0.0	0.0	-0.1	0.0
S5	low	EU incl. Fr	-0.2	-0.1	0.4	0.0	0.1
S5	medium	Fr	-0.5	-0.3	0.7	0.4	0.3
S5	medium	EU excl. Fr	0.3	0.1	-0.2	-0.4	-0.1
S5	medium	EU incl. Fr	-0.2	-0.2	0.5	0.0	0.2
S5	high	Fr	-0.5	-0.3	1.1	0.2	0.5
S5	high	EU excl. Fr	0.6	0.2	-1.0	-0.1	-0.2
S5	high	EU incl. Fr	0.1	0.0	0.1	0.1	0.2

Table D.3: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 15y w/o prolongation

State	Prob-ability	Region	Invest Costs	Fixed O&M Costs	Var. Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
S1	low	Fr	0.1	0.0	0.2	-0.2	0.0
S1	low	EU excl. Fr	0.1	-0.1	-0.3	0.2	0.0
S1	low	EU incl. Fr	0.2	-0.1	-0.1	0.0	0.0
S1	medium	Fr	0.0	0.0	0.1	-0.1	0.0
S1	medium	EU excl. Fr	0.1	0.0	-0.1	0.1	0.0
S1	medium	EU incl. Fr	0.1	0.0	0.0	0.0	0.0
S1	high	Fr	0.0	0.0	0.0	0.0	0.0
S1	high	EU excl. Fr	0.0	0.0	0.0	0.0	0.0
S1	high	EU incl. Fr	0.0	0.0	0.0	0.0	0.0
S2	low	Fr	0.1	0.0	0.2	-0.3	0.0
S2	low	EU excl. Fr	0.0	-0.1	-0.2	0.3	0.1
S2	low	EU incl. Fr	0.1	-0.1	0.0	0.0	0.0
S2	medium	Fr	0.0	0.0	0.1	-0.1	0.0
S2	medium	EU excl. Fr	0.0	0.0	0.0	0.1	0.0
S2	medium	EU incl. Fr	0.0	0.0	0.0	0.0	0.0
S2	high	Fr	0.0	0.0	0.0	-0.1	0.0
S2	high	EU excl. Fr	0.0	0.0	0.0	0.1	0.0
S2	high	EU incl. Fr	0.0	0.0	0.1	0.0	0.0
S3	low	Fr	2.6	0.3	-0.8	-2.5	-0.4
S3	low	EU excl. Fr	-0.2	0.1	-2.2	2.5	0.2
S3	low	EU incl. Fr	2.4	0.3	-2.9	0.0	-0.2
S3	medium	Fr	2.2	0.3	-0.6	-2.2	-0.4
S3	medium	EU excl. Fr	-0.1	0.1	-2.0	2.2	0.2
S3	medium	EU incl. Fr	2.1	0.3	-2.6	0.0	-0.2
S3	high	Fr	1.6	0.2	-0.5	-1.6	-0.3
S3	high	EU excl. Fr	0.0	0.1	-1.5	1.6	0.2
S3	high	EU incl. Fr	1.6	0.3	-2.0	0.0	-0.2
S4	low	Fr	1.4	0.2	0.0	-1.6	0.0
S4	low	EU excl. Fr	-0.8	-0.2	-0.7	1.6	-0.1
S4	low	EU incl. Fr	0.5	0.0	-0.6	0.0	-0.1
S4	medium	Fr	0.9	0.2	-0.1	-0.9	0.1
S4	medium	EU excl. Fr	-0.6	-0.1	-0.3	0.9	-0.1
S4	medium	EU incl. Fr	0.3	0.0	-0.4	0.0	-0.1
S4	high	Fr	0.1	0.0	-0.2	0.2	0.1
S4	high	EU excl. Fr	-0.3	-0.1	0.4	-0.1	-0.1
S4	high	EU incl. Fr	-0.1	0.0	0.2	0.0	0.0
S5	low	Fr	-0.1	0.0	-0.1	0.3	0.0
S5	low	EU excl. Fr	0.1	0.0	0.2	-0.3	0.0
S5	low	EU incl. Fr	-0.1	0.0	0.1	0.0	0.0
S5	medium	Fr	-0.5	-0.1	-0.2	0.8	0.1
S5	medium	EU excl. Fr	0.2	0.1	0.5	-0.8	0.0
S5	medium	EU incl. Fr	-0.3	0.0	0.3	0.0	0.0
S5	high	Fr	-1.2	-0.2	-0.3	1.8	0.1
S5	high	EU excl. Fr	0.6	0.2	1.0	-1.8	0.0
S5	high	EU incl. Fr	-0.6	0.0	0.6	0.0	0.1

Table D.4: Accumulated (discounted) system cost differences differentiated by cost categories in bn €$_{2010}$ (2010-2050): Cost of uncertainty – 0y w/o prolongation

State	Prob-ability	Region	Invest Costs	Fixed O&M Costs	Var. Costs	Trade Balance (Import Costs - Export Revenues)	Net Difference
S1	low	Fr	0.0	0.0	0.6	-0.7	-0.1
S1	low	EU excl. Fr	0.1	-0.2	-0.4	0.6	0.1
S1	low	EU incl. Fr	0.1	-0.2	0.2	0.0	0.1
S1	medium	Fr	0.0	0.0	0.5	-0.5	0.0
S1	medium	EU excl. Fr	0.0	-0.2	-0.3	0.5	0.1
S1	medium	EU incl. Fr	0.0	-0.2	0.2	0.0	0.1
S1	high	Fr	0.0	0.0	0.3	-0.4	0.0
S1	high	EU excl. Fr	0.0	-0.2	-0.1	0.4	0.1
S1	high	EU incl. Fr	0.0	-0.1	0.2	0.0	0.0
S2	low	Fr	0.0	0.0	0.0	-0.1	0.0
S2	low	EU excl. Fr	0.0	0.0	0.0	0.1	0.0
S2	low	EU incl. Fr	0.0	0.0	0.0	0.0	0.0
S2	medium	Fr	0.0	0.0	0.0	0.0	0.0
S2	medium	EU excl. Fr	0.0	0.0	-0.1	0.0	0.0
S2	medium	EU incl. Fr	0.0	0.0	-0.1	0.0	0.0
S2	high	Fr	0.0	0.0	-0.1	0.1	0.0
S2	high	EU excl. Fr	0.0	0.0	0.0	-0.1	0.0
S2	high	EU incl. Fr	0.0	0.0	0.0	0.0	0.0
S3	low	Fr	9.0	1.0	-0.9	-5.4	3.7
S3	low	EU excl. Fr	-0.1	0.3	-5.3	5.5	0.3
S3	low	EU incl. Fr	8.9	1.3	-6.2	0.0	4.0
S3	medium	Fr	5.8	0.8	-1.0	-3.3	2.2
S3	medium	EU excl. Fr	-0.2	0.2	-3.3	3.3	0.0
S3	medium	EU incl. Fr	5.6	0.9	-4.4	0.0	2.2
S3	high	Fr	0.0	0.0	0.0	0.1	0.0
S3	high	EU excl. Fr	0.0	0.0	0.0	-0.1	0.0
S3	high	EU incl. Fr	0.0	0.0	-0.1	0.0	0.0
S4	low	Fr	15.5	1.2	-4.1	-7.6	5.0
S4	low	EU excl. Fr	-1.0	0.1	-6.5	7.7	0.3
S4	low	EU incl. Fr	14.5	1.3	-10.6	0.0	5.2
S4	medium	Fr	11.8	0.7	-4.6	-3.7	4.3
S4	medium	EU excl. Fr	-0.4	0.1	-3.4	3.7	0.1
S4	medium	EU incl. Fr	11.4	0.9	-8.0	0.0	4.4
S4	high	Fr	-0.8	-0.3	-0.7	1.9	0.1
S4	high	EU excl. Fr	0.4	0.2	1.3	-1.9	0.0
S4	high	EU incl. Fr	-0.3	-0.1	0.6	0.0	0.1
S5	low	Fr	-1.4	-0.2	-0.4	2.2	0.2
S5	low	EU excl. Fr	0.6	0.2	1.4	-2.1	0.0
S5	low	EU incl. Fr	-0.8	0.0	1.0	0.0	0.2
S5	medium	Fr	-3.6	-0.7	-0.7	6.1	1.1
S5	medium	EU excl. Fr	1.2	0.3	4.5	-6.1	-0.2
S5	medium	EU incl. Fr	-2.5	-0.4	3.7	0.0	0.9
S5	high	Fr	-9.3	-1.3	6.8	10.1	6.4
S5	high	EU excl. Fr	1.5	0.2	7.9	-10.1	-0.5
S5	high	EU incl. Fr	-7.7	-1.1	14.7	0.0	5.8

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Curriculum Vitae

Raimund Malischek

Personal Details

Date of Birth	February 9th, 1985
Place of Birth	Munich, Germany

Education

Ph.D. student	since April 2011
University of Cologne	*Cologne, Germany*
Diploma in Mathematics	2010
Ludwig-Maximilians-Universität München (LMU)	*Munich, Germany*
Study Abroad Programme	2008
University Leiden	*Leiden, The Netherlands*
University Entrance Examination (Abitur)	2004
Gymnasium Grafing	*Grafing, Germany*

Professional Experience

Energy Analyst	since March 2016
International Energy Agency (IEA)	*Paris, France*
Research Associate	2011-2016
Institute of Energy Economics at the University of Cologne (EWI)	*Cologne, Germany*
Secondee	2015
International Energy Agency (IEA)	*Paris, France*
Secondee	2014
International Energy Agency (IEA)	*Paris, France*

Refereed Journal Publications

Knaut, A., Lindenberger, D., Malischek, R., Paulus, S., Tode, C., Wagner, J., 2016. The reference forecast of the German energy transition - An outlook on electricity markets. Energy Policy, Vol.92:477-491.

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Conferences

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20th Spring Meeting of Young Economists, 2015, Ghent/Belgium.

28th Annual Congress of the European Economic Association, 2013, Gothenburg/Sweden.

13th European IAEE Conference, 2013, Düsseldorf/Germany.

8th Conference on Energy Economics and Technology, 2013, Dresden/Germany.