Modelling and Analysis of Global Coal Markets

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Contents

List of Figures

List of Tables

Abbreviations

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ANFO	Ammonium Nitrate Fuel Oil
APX	Amsterdam Power Exchange
ARA	Amsterdam, Rotterdam, Antwerp (port region)
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BLS	Bureau of Labor Statistics (United States)
CIF	Cost, Insurance, Freight (Incoterm)
CMR	Chinese Ministry of Railways
CO_2	Carbon Dioxide
CoAL	Coal of Africa Ltd.
DANE	Departamento Administrativo Nacional de Estadistica (Colombia)
DIME	Dispatch and Investment Model for Electricity Markets in Europe
EEX	European Energy Exchange
EIA	Energy Information Administration
ESMAP	Energy Sector Management Assistance Program
EUR	Euro
EWI	Energiewirtschaftliches Institut an der Universität zu Köln (Institute of Energy Economics at the University of Cologne)
FOB	Free On Board (Incoterm)
FOC	First Order Condition
GAMS	General Algebraic Modelling System
GHG	Greenhouse gas
HVDC	High Voltage Direct Current
IEA	International Energy Agency

IMAR	Autonomous Republic of Inner Mongolia
JSM	Japanese Steel Mills
KKT	Karush-Kuhn-Tucker Conditions
LCP	Linear Complementarity Programme
LNG	Liquefied Natural Gas
LRMC	Long Run Marginal Costs
MCIS	McCloskey Coal Industry Services
MCP	Mixed Complementarity Problem
MIT	Massachusetts Institute of Technology
MJ	Mega joule
MPEC	Mathematical Programme with Equilibrium Constraints
MSE	Mean Squared Error
Mt	Million tonnes
Mtpa	Million (metric) tonnes per annum
MWh	Mega Watt hour
NBS	National Bureau of Statistics (China)
NDRC	National Development and Reform Commission (China)
NLP	Non-linear Programme
NO_x	Mono-nitrogen Oxides
NSW	New South Wales (Australia)
OC	Open-cast (mine)
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
OPEC	Organisation of the Petroleum Exporting Countries
PC	Perfect Competition
PCI	Pulverised-Coal-Injection
POSCO	Pohang Iron and Steel Company
PRB	Powder River Basin (United States)
PRC	People's Republic of China
QLD	Queensland (Australia)
RMSPE	Root Mean Squared Percentage Error
t	Tonne
TRCSC	Chinese Taxation Regulation Commission of the State Council

U.S.	United States
UG	Underground (mine)
USD	United States Dollar
VDKI	Verein der Kohleimporteure (Hard coal importers' association)
WCM	World Coal Model
w.r.t	with respect to

Chapter 1

Introduction

1.1 Motivation

Coal is the most abundant of all fossil fuels. In energy terms, the current coal reserves are around 3.2 times larger than those of natural gas and 2.5 times larger than those of oil (IEA, 2011c). Moreover, coal reserves are widely dispersed around the globe and thus coal supply is much less affected by geo-political tensions.

Given that supply costs of coal have also been, in energy terms, much lower than those of oil and natural gas, coal has always played a key role in energy markets, especially in the power generation sector. In 2010 more than 40% of the global electricity generation was coal-based (IEA, 2012). Besides its role in the power sector, coal – so-called metallurgical coal – is also an important input in steel-making. According to the World Coal Association, around 70% of the steel produced worldwide relies on coal as a crucial input (WCA, 2011).

Although conventional wisdom suggests that coal is a fuel from the olden days, coal demand has been escalating in recent years; coal accounted for almost half of the incremental global primary energy use in the decade from 2000 to 2010. Hence, worldwide coal use grew nearly as fast as oil, natural gas, and renewable energy consumption together (IEA, 2011c). This growth in coal use can almost entirely be attributed to developing and transition economies, with China and India at the forefront.

These dynamic developments have reshaped global coal markets markedly and thus also changed their underlying economics. While coal used to be a predominantly domestic fuel, the share of internationally traded coal has increased continuously, with the sharpest growth rates encountered in the last decade. Furthermore, prices for internationally traded coal soared around 2006, reached record levels in 2008, and remained relatively high through 2010 and 2011.

The supply-side has reacted to the changing market environment. Some countries, especially China and Indonesia, have tightened governmental control over their coal exporting sectors and have introduced classic instruments of strategic trade policy. Moreover, giant multinational mining companies, which hold large coal export capacities, have benefited from the changing market structures and managed to receive high prices for their coals. There are doubts that the allocation and pricing of coal have been competitive in recent years both regarding the market for steam coals and the market for metallurgical coals.

At the same time, China, the world's largest consumer and producer of coal, shifted from being a net-exporter of coal to being a net-importer of coal within a few years. Due to the sheer size of the Chinese coal market, comparably small changes in the Chinese energy system or the Chinese economy in general can have substantial repercussions on the international coal trade. These repercussions impact power markets and steel industries across the globe. This is obvious for China, with its centrally planned energy system, but also holds true for other large domestic coal markets like the United States. Therefore, studying the interaction between domestic energy systems and international coal markets is important both from a short-term and a long-term perspective.

In light of the dynamic evolution of coal markets in recent years and the importance of coal in the global energy system (and steel markets), the question of how coal markets work and how they are organised naturally arises. Therefore, this thesis firstly seeks to make a contribution to explaining recent coal market outcomes and thereby enhancing the understanding of the drivers of coal markets. The analysis covers both the market for steam coal and the thus far rather neglected market for metallurgical coal. This is the base for hypotheses on how these markets could evolve in the future. Secondly, this thesis addresses the special role of China in global coal markets. As Chinese planning authorities' decisions affect the global energy system, a thorough understanding of China's role is key in understanding coal market economics. The Chinese energy system is still in transition and therefore studying China's role is as relevant for today as for the future. In pursuing the analysis, this thesis presents various computer-based models that allow reproduction of recent market equilibria, as well as projection of future market equilibria, taking into account the dynamics of the market.

Undoubtedly, global energy needs will continue to grow and coal is likely to remain a cornerstone of the global energy system for many years to come (IEA, 2011c). Therefore, understanding both the long and short-term economics of global coal markets is crucial for investors, decision-makers, and environmentalists worldwide. The provision of affordable and secure energy will need substantial investment as well as support from appropriate policies. Furthermore, the combustion of coal is thought to be a key driver of global warming. Hence, any policy targeted at mitigating climate change will have to take into account coal market economics in order to be effective.

1.2 Modelling Spatial Markets

The coal market's key feature is its spatial structure, i.e. coal production is geographically separated from coal consumption and individuals incur transportation costs in clearing the market. Coal has a low value-to-weight ratio and thus haulage costs can be substantial. The spatial structure and the role of transportation costs lead to different market outcomes than a spaceless model would imply. In a perfectly competitive market the law of the uniform price does not hold if transportation costs differ. In a non-competitive market the geographical separation of supply and demand may give players the ability to price-discriminate over space.

Modelling spatial market equilibria has a long-standing tradition in economics and particularly in operations research. Pioneering research by Hitchcock (1941), Kantorovich (1942), and Koopmans (1949) centred around the linear programming transportation problem. Essentially, this problem deals with the least-cost allocation of a good between spatially separated (fixed) demand and production. Enke (1951) developed an analogue between spatial markets and electric circuits (Kirchhoff's laws). Samuelson (1952) proceeds from Enke's formulation and shows how the least-cost transportation problem can be converted into a maximisation problem and solved with linear programming methods. Takayama and Judge (1964, 1971) further developed Samuelson's spatial equilibrium model and extended it to the spatial monopoly case. Later the approach was generalised to the Cournot case, for instance by Kolstad and Abbey (1984), Kolstad and Burris (1986), and Harker (1984, 1986a), and for the Stackelberg case, for instance by Nelson and McCarl (1984) or Miller et al. (1991).

1.2.1 Mathematical Programming Approach

Classic methods of optimisation often reach their limits when it comes to modelling imperfect competition. Modelling non-competitive behaviour in spatial markets typically implies that more than one market participant optimises an objective function. The equilibrium is then characterised by the requirement that the market clearing vector of variables fulfils the first-order-condition (FOC) of each market participants' objective function simultaneously. This is the core of complementarity programming and the reason why these methods have been used extensively in modelling imperfect competition in spatial markets.

The models presented in this thesis rely either explicitly on complementarity programming methods (chapters 2, 3, 4, and 5) or implicitly use complementarity programming to state the equilibrium conditions of a Mathematical Programme with Equilibrium Constraints (chapter 2). Complementarity programming is based on the Karush-Kuhn-Tucker (KKT) conditions. The KKT conditions characterise the optimal solution of an optimisation problem which consists of equations and inequalities. The KKT conditions can be explained using the following simple maximisation problem. Let $f(x)$ be a concave function to be maximised, e.g. a profit function, and $g(x) = a - x \geq 0$ a convex restriction, e.g. a production capacity limit. The Lagrangian Z of the problem is then defined as $Z = f(x) + y(a - x)$ with y being the Lagrangian multiplier of $g(x)$. The KKT conditions of this problem can be expressed as follows:

$$\partial Z/\partial x = f'(x) - y \leq 0, \qquad x \geq 0, \qquad x \cdot \partial Z/\partial x = 0 \tag{1.1}$$

$$\partial Z/\partial y = a - x \geq 0, \qquad y \geq 0, \qquad y \cdot \partial Z/\partial y = 0 \tag{1.2}$$

As figure 1.1 shows, there are four candidates M for a maximum of the above outlined optimisation problem that all fulfil the corresponding KKT conditions. In case (I), M is characterised by $f'(x) = 0$ and $x > 0$, as well as $y = 0$ (restriction $g(x)$ is non-binding), hence $x \cdot \partial Z/\partial x = 0$ and $y \cdot \partial Z/\partial y = 0$ hold. In case (II) $f'(x) = 0$ and $x = 0$ as well as $y = 0$ hold, and hence $x \cdot \partial Z/\partial x = 0$ and $y \cdot \partial Z/\partial y = 0$ hold too. In case (III) the KKT point is similar to case (II) but $f'(x) < 0$. Since $x = 0$, $x \cdot \partial Z/\partial x = 0$ still holds. Case (IV) is probably the most interesting one. Here M is characterised by $f'(x) > 0$ and $x > 0$ as well as $\partial Z/\partial y = 0$. For $x \cdot \partial Z/\partial x = 0$ to be fulfilled, $y = f'(x)$ has to hold. Consequently, y is the shadow-price of restriction $g(x)$.

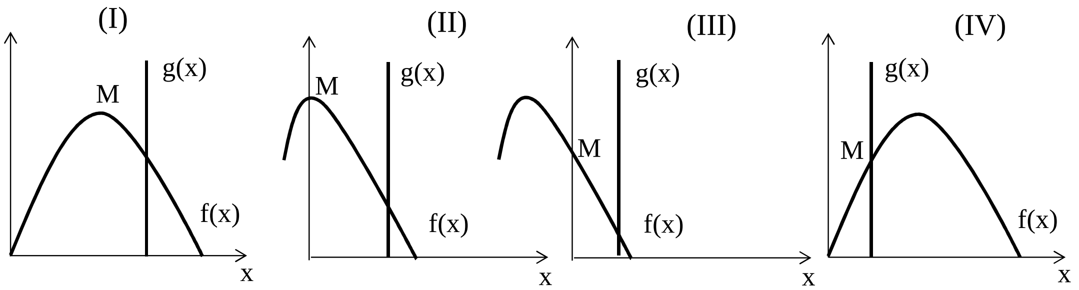

FIGURE 1.1: KKT-point candidates

In terms of the above outlined optimisation problem $f'(x)$ corresponds to marginal profit and y can be interpreted as the value of the marginal unit of production capacity. All four possible candidates for maxima fulfil all KKT conditions simultaneously. Hence, the KKT conditions constitute the first-order necessary conditions of an optimisation problem with non-negative choice variables. Furthermore, the Kuhn-Tucker sufficiency theorem states that for a maximisation problem a KKT point is a global maximum and the KKT conditions are *necessary-and-sufficient* if the following specifications are satisfied (see Chiang, 1984):[1]

- the objective function is differentiable and *concave* in the non-negative orthant

[1]The Arrow-Enthoven sufficiency theorem relaxes the concavity-convexity requirements of the Kuhn-Tucker sufficiency theorem to *quasi*concavity and *quasi*convexity but require additional conditions to be met (see Arrow and Enthoven, 1961).

- each constraint function is differentiable and *convex* in the non-negative orthant
- the KKT first-order conditions are all satisfied simultaneously

Complementarity modelling techniques are also useful when one seeks to optimise an objective function subject to a system of equilibrium constraints. Such a problem is typically called a Mathematical Programme with Equilibrium Constraints (MPEC). Essentially, MPECs are constrained non-linear programmes (NLP) and can be solved as such. With slight modifications of the above example, the MPEC modelling approach can be cast as follows:

Maximise

$$S(z, x) \tag{1.3}$$

subject to:

$$h(z) \geq 0 \tag{1.4}$$

$$z, x, y \geq 0 \tag{1.5}$$

$$\partial f(z, x)/\partial x - y \cdot g'(x) \leq 0 \perp x \geq 0 \tag{1.6}$$

$$g(x) \geq 0 \perp y \geq 0 \tag{1.7}$$

The outlined MPEC can be interpreted as a sequential-move Stackelberg model with $S(z, x)$ being the profit function of a Stackelberg leader whose profits depend on his own output z and his follower's output x. The follower's profits $f(z, x)$ depend on his output decision x and the leader's output z. The leader decides on his output first and thereby takes into account the (complementarity) FOCs of the follower and his own production capacity constraint $h(z)$ when maximising his objective function. An MPEC is typically not a convex programme which could potentially lead to irregularities in the feasible region. Convergence of solvers has improved substantially, particularly when the orginal MPEC is reformulated to alternative NLPs. Yet, the problem of spurious stationary points can still complicate the solution of MPECs.

1.2.2 Accuracy, Assumptions, Caveats, and Limitations

The major characteristic of a spatial market is the allocation of a good between geographically separated participants. Therefore, assessing whether the models are able to reproduce real-market trade-flows either qualitatively (chapters 3 and 5), or in a more rigorous way, by applying statistical measures (chapters 2 and 4), is a key component of the analyses presented in this thesis. Besides the validation of the primal variables (typically trade-flows), the validation of the models' dual variables, i.e. the regional price levels, are another aspect of the prediction quality assessment.

The analyses in this thesis are based on a unique dataset that covers a wide range of coal market parameters in great detail. Although coal market data was gathered with due diligence and edited with care, the heterogeneity of the sources, the comparably long time-spans, and data-complexity, as well as the scope of the data needed, inevitably result in some noise and bias. Similar issues potentially apply to the data and statistics compiled by other institutions and organisations that were used as input data or in validating the models. Furthermore, in some cases, limited data availability required assumptions on missing data points. All of these aspects could lead to distortions and biases in the model results and validation.

The models are based on the assumption that competition is in quantities in coal markets. Capacity constraints are relevant in coal markets and therefore one would expect quantities to be the strategic variable (see Kreps and Scheinkman, 1983). Moreover, in a bulk-commodity industry that runs on production and export targets and a demand side that is relatively price-inelastic, this assumption does not appear to be too problematic. Yet, it should be clear that competition in prices could lead to different results.

A common critique of partial equilibrium modelling as applied in this thesis is that a wide range of seemingly plausible market outcomes can be (re-)produced by arbitrarily varying conduct or data assumptions, e.g. parameters of the inverse demand function. Indeed, the equilibrium modelling approach gives the developer several degrees of freedom regarding model calibration. This problem is typically aggravated by limited data availability for long range back-testing of the model results. Given the large size of the problem-set regarding the number of market participants and their supply and demand parameters, the data limitations for other methods and/or long range back-testing are evident. For instance, data in a yearly resolution is usually the best one can obtain. In this regard, partial equilibrium modelling is often the only conclusive approach to analysing such markets. The inherent degrees of freedom of the approach are therefore both a blessing and a curse.

Generally the problem of limited long range back-testing can be mitigated by validating model results for a few recent years. A variety of model assessment tools are available and should preferably be used and interpreted in concert to cover a wide range of prediction accuracy aspects. Assessing primal *and* dual variables is compulsive as they are closely linked. A good fit in only one of them is inconclusive. Moreover, the allegation of arbitrariness can typically be overcome by flanking numerical results with realistic qualitative backing of the underlying assumptions. Finally, some cases call for a sensitivity analysis regarding key parameters to check for the robustness of the numerical results (chapters 2 and 3).

In this respect, future research could combine equilibrium modelling techniques with other methods to overcome arbitrariness of data assumptions. For instance, econometric techniques could help gaining insights into the price responsiveness of coal demand and could be used to estimate the parameters of the demand functions.

Another common critique of the approach applied in this thesis is its static nature. The analyses in chapters 2 to 4 are essentially snap-shots of the market structure of the coal trade in recent years. The strategic interaction of players is modelled as one-shot games although, in reality, the players interact repeatedly. This causes two problems: first, the results are simply best-supply equilibria and cannot explain the investment in capacities. Second, the best-supply equilibria might be biased in a sense that in a repeated game the outcome might differ from the one-shot game equilibrium. For instance, depending on the time preference of the players, repeated interaction might lead to implicit collusion.

The latter problem is not so severe in coal markets and can sometimes be overcome by explicitly modelling cooperative and non-cooperative outcomes (see chapter 2). Neglecting the capacity investment equilibrium is a more serious issue in a market where capacity constraints are relevant. In this case however, the approach is justified as the market structure evolved exogenously due to the dynamic development of the global coal market in recent years. Yet an analysis with a short or medium-term outlooking focus where both strategic behaviour and capacity investment matter would have to take into account strategic capacity planning. Modelling such games is however still computationally expensive.

Nevertheless computational tractability advances rapidly in this field. State-of-the-art methods might already allow solution of two period games, with supply and investment as strategic variables, in a system with a manageable size such as the market for metallurgical coals. Modelling endogenous market structure evolution in the medium-term future could be another interesting avenue for future research.

Hence, in light of the caveats and limitations, the goal of applying spatial equilibrium models to global coal markets cannot be producing high resolution and high precision results. Typically, the approach applied in this thesis only provides trajectories and ranges for assessing real market outcomes. Therefore, the goal is rather to understand the drivers and mechanisms of the market and to assess whether a specific market structure performs systematically and robustly better than another.

1.3 Organisation of the Thesis

The thesis comprises four interrelated essays featuring modelling and analysis of coal markets. Each of the four essays has a dedicated chapter in this thesis. Chapters 2 to 4 have, from a topical perspective, a backward-looking focus and deal with explaining recent market outcomes in the international coal trade. The findings of those essays may serve as guidance for assessing current coal market outcomes as well as expected market outcomes in the near to medium-term future. Chapter 5 has a forward-looking focus and builds a bridge between explaining recent market outcomes and projecting long-term market equilibria. The body of this thesis is structured as follows:

Chapter 2, *Strategic Behaviour in International Metallurgical Coal Markets* (see Trüby, 2013), deals with market conduct of large exporters in the market of coals used in steel-making in the period 2008 to 2010.[2] I am the sole contributor to this work. In this essay I analyse whether prices and trade-flows in the international market for metallurgical coals were subject to non-competitive conduct in the period 2008 to 2010. To do so, I develop mathematical programming models – a Stackelberg model, two varieties of a Cournot model, and a perfect competition model – for computing spatial equilibria in international resource markets. Results are analysed with various statistical measures to assess the prediction accuracy of the models. The results show that real market equilibria cannot be reproduced with a competitive model. However, real market outcomes can be accurately simulated with the non-competitive models, suggesting that market equilibria in the international metallurgical coal trade were subject to the strategic behaviour of coal exporters.

Chapter 3 and chapter 4 deal with market power issues in the steam coal trade in the period 2006 to 2008. Steam coals are typically used to produce steam either for electricity generation or for heating purposes. This research strand was jointly developed and pursued with Moritz Paulus.

In Chapter 3 we analyse market behaviour of key exporting countries in the steam coal trade. This chapter features the essay *Market Structure Scenarios in International Steam Coal Trade*[3] (see Trüby and Paulus 2012). I am the leading author of this essay. In the presented paper, we analyse steam coal market equilibria in the years 2006 and 2008 by testing for two possible market structure scenarios: perfect competition and an oligopoly setup with major exporters competing in quantities. The assumed oligopoly scenario cannot explain market equilibria for any year. While we find that the competitive model simulates market equilibria well in 2006, the competitive model is not able to reproduce real market outcomes in 2008. The analysis shows that not all available supply capacity was utilised in 2008. We conclude that either unknown capacity bottlenecks or more sophisticated non-competitive strategies were the cause for the high prices in 2008.

Chapter 4 builds upon the findings of the analysis in chapter 3 and adds a more detailed representation of domestic markets. The corresponding essay is titled *Nations as Strategic Players in Global Commodity Markets: Evidence from World Coal Trade* of

[2]This article is copyrighted and reprinted by permission. The presented article first appeared in *Energy Economics*, Vol. 36.

[3]This article is copyrighted and reprinted by permission from the International Association for Energy Economics. The presented article first appeared in *The Energy Journal*, Vol. 33, No. 3. Visit *The Energy Journal* online at http://www.iaee.org/en/publications/journal.aspx.

which I am a contributing author (see Paulus et al., 2011). In this chapter we explore the hypothesis that export policies and trade patterns of national players in the steam coal market are consistent with non-competitive market behaviour. We test this hypothesis by developing a static equilibrium model which is able to model coal producing nations as strategic players. We explicitly account for integrated seaborne trade and domestic markets. The global steam coal market is simulated under several imperfect market structure setups. We find that trade and prices of a China - Indonesia duopoly fits the real market outcome best and that real Chinese export quotas in 2008 were consistent with simulated exports under a Cournot-Nash strategy.

Chapter 5 looks at the long-term effect of Chinese energy system planning decisions. The time horizon is 2006 to 2030. The analysis in this chapter combines a dynamic equilibrium model with the scenario analysis technique. The corresponding essay is titled *Coal Lumps vs. Electrons: How Do Chinese Bulk Energy Transport Decisions Affect the Global Steam Coal Market?*[4] (see Paulus and Trüby, 2011). I am a contributing author to this essay. The essay demonstrates the ways in which different Chinese bulk energy transport strategies affect the future steam coal market in China and in the rest of the world. Increasing Chinese energy demand will require additional energy to be transported from the supply to the demand regions. If domestic transport costs escalate, Chinese coal consumers could increasingly import coal. We analyse two settings: one in which coal is increasingly transported by rail and one in which coal energy is transported as electricity. A key finding is that if coal were converted into electricity early in the supply chain, worldwide marginal costs of coal supply would be lower than if coal were hauled by train. Furthermore, China's dependence on imports is significantly reduced in this context. Allocation of welfare changes particularly in favour of Chinese consumers while rents of international producers decrease.

[4]This article is copyrighted and reprinted by permission. The presented article first appeared in *Energy Economics*, Vol. 33, No. 6.

Chapter 2

Strategic Behaviour in International Metallurgical Coal Markets

2.1 Introduction

Economies all over the world crucially rely on commodities that are procured from international resource markets. One category is energy resources such as imported natural gas and thermal coal for electricity generation or crude oil for petroleum production. Another field is natural resources and minerals that are essential in industrial production: iron ore for steel making, lithium for batteries, bauxite for aluminium production, or rare earth elements for various high-tech products to name but a few. Recent price spikes for such commodities have given rise to concerns about security and reliability of supply of natural resources. Moreover, many markets for natural resources and minerals are highly concentrated and do not appear to be competitively organised at first glance.

The international metallurgical coal (or coking coal) trade – metallurgical coal is a key input in steel-making – is another such example.[5] Prices for this coal variety have reached record levels in recent years and the market structure is oligopolistic. Specifically, four giant multinationals, BHP-Billiton, Rio Tinto, Anglo-American, and Xstrata (henceforth the "Big-Four"), together control around 50% of the global metallurgical coal export capacity. The Big-Four produce their metallurgical coal in Australia and compete against a handful of smaller players mainly from Canada, the United States, and Russia.

[5] Metallurgical coals (hard coking coal, semi-soft coking coal, Pulverised-Coal-Injection coal) are used to produce the coke utilised in blast furnaces or as in the case of Pulverised-Coal-Injection (PCI) coal, to reduce the consumption of coke in blast furnaces. Often the terms metallurgical coal and coking coal are used interchangeably, although strictly speaking PCI coals are not necessarily coking coal. Metallurgical coal is distinct from thermal (or steam) coal which is typically used to produce electricity or heat.

In the context of the oligopolistic market structure and the high prices in recent years, the presented paper seeks to shed light on the question of whether metallurgical coal prices were indeed subject to non-competitive market conduct and if so, which strategy may have prevailed in reality. It is *a priori* unclear which model of oligopoly captures the characteristics and market conduct in the international metallurgical coal trade best. Therefore the analysis comprises four different strategies with regard to the oligopolists' output decision: first, assuming quantities to be the strategic variable and exporters to engage in Cournot-Nash competition is the obvious baseline scenario (henceforth "Cournot oligopoly" scenario). Second, there are also specific market characteristics that suggest a first mover advantage of the Big-Four in this market. The key price in the international metallurgical coal trade is the so-called "hard coking coal benchmark price". This price, and the corresponding delivery-contracts, is regularly determined in negotiations between major Australian exporters, essentially the Big-Four, and large Asian steel mills. Other exporters subsequently use this benchmark price for their pricing, subject to their respective coal qualities (Bowden, 2012, Chang, 1997).

Although the benchmark price is mostly set by BHP-Billiton, the other three multinationals set the price occasionally too, and the Big-Four provide mutual support in enforcing this price (McCloskey, 2012a).[6] There is no hard evidence for the Big-Four cooperatively determining the benchmark price but the revolving system of individual companies setting the price suggests that there is a potential for (tacit) collusion. To account for the potential first mover advantage and the possibility of collusion between the Big-Four I employ a Stackelberg model. In this model the Big-Four cooperatively determine their output in the benchmark price negotiations, taking into account the other exporters' reaction to their decision. Third, I combine the Cournot-Nash model with the hypothesis of collusive behaviour between the Big-Four. Specifically, I assume that the Big-Four determine their output cooperatively but simultaneously with their competitors (henceforth "Cournot cartel" scenario). Finally, various market characteristics can lead to perfectly competitive equilibria despite an oligopolistic market structure. Consequently, in the fourth scenario I test for perfectly competitive conduct of all players.

To test which of the outlined market structures explains the real market best I develop mathematical programming models in the presented paper – a Stackelberg model, two varieties of a Cournot model, and a perfect competition model – for computing

[6] This became obvious in recent negotiations between Anglo-American and the South Korean steel mill POSCO. As POSCO did not accept the benchmark price proposed by Anglo-American, the company refused to supply high quality coking coal to the steel maker for the whole quarter, supported by other exporters, most notably BHP-Billiton and Xstrata, who also refused to deliver this specific quality for the whole quarter (McCloskey, 2012a).

spatial equilibria in international resource markets. The models are applied to the international metallurgical coal trade in the period 2008 to 2010. The models for Cournot-style and perfectly competitive behaviour are implemented as Mixed Complementarity Programmes (MCP). The Stackelberg model is initially formulated as a Mathematical Programme with Equilibrium Constraints (MPEC) and then automatically reformulated as a standard non-linear programme to facilitate solution. The models are based on a detailed supply-side focused dataset comprising e.g. mining and transport costs of individual mines, seaborne freight rates and supply cost developments. As the price elasticity of demand is a key unknown in my analysis, I test for a large bandwidth of elasticity cases. Model prediction accuracy is assessed using various statistical measures like Theil's inequality coefficient, Spearman's rank correlation coefficient, and linear hypothesis testing. The numerical results suggest that market equilibria in the seaborne metallurgical coal market cannot be explained by perfectly competitive behaviour. However, the Stackelberg and the Cournot oligopoly scenarios reproduce market outcomes accurately. Departing from different market structure assumptions both models produce similarly convincing results for slightly different, but in any case realistic, ranges of elasticities.

Literature on market conduct in international coal markets is relatively scarce and most papers focus on thermal coal markets (e.g. Abbey and Kolstad, 1983, Haftendorn and Holz, 2010, Kolstad and Abbey, 1984, Trüby and Paulus, 2012). Yet, there are two notable exceptions, Bowden (2012) and Graham et al. (1999), who specifically deal with market power in the coking coal trade. Bowden (2012) is an excellent qualitative analysis of the history of the coking coal trade in the Pacific basin. The author investigates the rise and fall of a buying cartel in this market and describes the emergence of a powerful oligopoly of coking coal exporters since 2001. Graham et al. (1999) quantitatively analyse international metallurgical coal trade in the year 1996 using a mathematical programming model. The authors test for various non-competitive market structures and find that an all consumer oligopsony reproduces actual market data best.

The contribution of the presented paper is threefold: first, by modeling some players as a cooperative Stackelberg leader and implementing it as an MPEC, I apply a novel approach to resource market analysis, which potentially delivers insights for other markets as well. Second, I show that prices and trade-flows in the international metallurgical coal market are consistent with strategic behaviour by coal exporters in the period 2008 to 2010. Third, by extending the analysed period to three years and using most recent data, I am updating the research started by Graham et al. (1999) and provide empirical evidence for Bowden (2012) most recent findings with regard to market power exertion of large resource companies.

The remainder of the presented paper is organised as follows: section 2.2 briefly introduces the international metallurgical coal market. Section 2.3 describes the models developed in this paper. The data is presented in section 2.4. The statistical measures used to validate the models are described in section 2.5. Results are shown in section 2.6. Section 2.7 discusses the results and section 2.8 concludes the paper.

2.2 The Seaborne Metallurgical Coal Market

Supply-side market power is a rather recent phenomenon in the metallurgical coal market. For more than 40 years the metallurgical coal trade, especially in the Pacific basin, was characterised by a buying cartel keeping prices low. The Japanese Steel Mills (JSM), one of the world's largest metallurgical coal consumers, was the core of this cartel. The JSM's trade strategies were underpinned by other Asian steel mills, mainly from South Korea and Chinese Taipei, subordinating to the negotiations led by the JSM. From a strategic perspective, the buying cartel faced a trade-off between constantly driving down prices at the risk of making some mining operations unprofitable and paying a price premium to maintain a diversified procurement portfolio (Bowden, 2012).

A phase of unsustainably low coking coal prices during the 1990s resulted in an exit of producers and a wave of industry consolidation striving for efficiency gains. This reversed the market structure and, by the early 2000s, the JSM faced an oligopoly of large and efficient mining companies. Bowden (2012, p.19) for example concludes that *"the shift to a seller's market, dominated by a handful of giant mining conglomerates – BHP-Billiton, Rio Tinto, Xstrata (formerly Glencore), and Anglo-American in Australia and the Fording-Teck consortium in Canada – was confirmed in the decade after the 2001 price increases."*

The consolidation on the supply side was complemented by a sharp increase in demand for metallurgical coal from entrant Chinese and Indian steel mills that have so far not subordinated to the JSM's pricing policy and hence may have further eroded buyer-side market power. These structural changes were paralleled by steeply rising hard coking coal benchmark prices since the mid-2000s. In recent years, hard coking coal benchmark prices reached an unprecedented 300 USD/t in 2008, plummeted to 129 USD/t in 2009 and rose to 227 USD/t in 2010.[7]

In this context the Germany-based coal importer's association VDKI notes in their annual report (VDKI, 2011, p.24) that *"the small number of coking coal producers is essentially an oligopoly which is able to dictate prices...with relatively little effort."* The Big-Four are thought to have substantial market power due to good coal qualities, large

[7] All prices FOB ("Free On Board") Australia.

TABLE 2.1: Market shares in the international metallurgical coal trade, 2010

	Australia	Canada	Russia	USA	Other	*Total*
Europe and Mediterranean	8.4%	2.0%	1.7%	11.3%	0.3%	23.7%
Japan	18.7%	3.5%	0.9%	1.1%	0.2%	24.3%
Korea	7.1%	2.2%	0.5%	1.1%	0.3%	11.1%
Chinese Taipei	3.0%	0.3%	0.0%	0.1%	0.0%	3.4%
China	8.9%	1.8%	1.0%	1.6%	0.5%	13.7%
India	13.1%	0.0%	0.0%	0.9%	0.0%	14.1%
Brazil	1.7%	0.7%	0.0%	2.9%	0.0%	5.3%
Other Latin America	0.6%	0.2%	0.0%	0.4%	0.3%	1.5%
Other	1.4%	0.1%	0.1%	0.1%	1.0%	2.7%
Total	63.0%	10.7%	4.3%	19.5%	2.6%	100.0%

Source: IEA (2011a).

export capacities and their close location to the main importers.[8] This hypothesis is not only backed by soaring prices but also by the fact that recently a single company, BHP-Billiton, pushed the pricing system away from annual contracts towards a quarterly and then monthly benchmarking mechanism – despite heavy resistance from steel mills (McCloskey, 2009, 2011). The Big-Four compete with metallurgical coal exporters from several other countries. In most countries (Canada, Russia, New Zealand, Poland, Indonesia, and South Africa) there is only one dominant company that exports metallurgical coals. In the United States, the main export port for metallurgical coal (Lambert's Point, Norfolk, Virginia) and the railway lines serving the ports are controlled by one player suggesting market power exertion via the infrastructure.[9]

Metallurgical coals are traded both domestically and internationally. With a market volume of 245 million tonnes (mt), roughly a quarter of the global production (891 mt) was traded internationally (almost exclusively seaborne, using dry bulk vessels) in 2010.[10] Interactions between the domestic markets and the international market are minor in the metallurgical coal trade. Domestic metallurgical coal producers are usually separated from the export market due to coal quality, contractual obligations, export regulations (e.g. quotas or licences), as well as a lack of access to export infrastructure.

[8]The exertion of market power may be supported by important barriers to entry and capacity expansion restrictions in the metallurgical coal market. High political risk and/or the lack of financial resources and technical capability are effective barriers to solo market entry of developing countries with so far untapped metallurgical coal resources. Furthermore, export capacity expansion usually requires coordination of infrastructure and mining capacity upgrading with different stakeholders being involved – a very time consuming process (for details and examples see IEA, 2011b). Such restrictions are particularly delaying for greenfield projects which also need the construction of export infrastructure. A good example is Mozambique where metallurgical coal projects have been underway since around 2005; the first small-scale coal shipments began in 2011 but sizeable coal exports are not to be expected before 2016 (IEA, 2011b).

[9]US coal exporters have regularly alluded that the railway operators influence exports strongly through rail rates. Rail rates can fluctuate by 300% depending on market conditions (McCloskey, 2012b,c). Moreover, several analyses have argued that in the United States' coal markets market power is exerted via the infrastructure (e.g. Wolak and Kolstad, 1988).

[10]Unless otherwise stated all figures in this section refer to the year 2010 and stem from IEA (2011a).

The key countries in the seaborne metallurgical coal market are clearly Australia and Japan with an export share of 63% and an import share 24% respectively (table 2.1). The second largest exporting country is the United States with a market share of around 20%, followed by Canada with a market share of around 11%. Small exporting countries, with market shares below 5% are Russia, Colombia, Indonesia, South Africa and New Zealand. Besides Japan, major importing regions are Europe and the neighbouring Mediterranean countries (24%), India (14%), China (14%), and South Korea (11%).

2.3 Model Description

In this section I develop three spatial market models – Cournot-Nash behaviour, perfect competition, and Stackelberg leadership – for typical resource markets in which exporters and importers trade with each other. Although these models are based on specific fundamental data for the seaborne metallurgical coal market in this analysis, the basic model structure could also be used for analysing other spatial natural resource markets or, for instance, agricultural products' markets.[11]

The modelling approach for competitive and Cournot-Nash equilibria (sections 2.3.1 and 2.3.2) dates back to Samuelson (1952), with his work on the programming of competitive equilibria in spatial markets, and was generalised for various non-competitive market structure scenarios, e.g. by Takayama and Judge (1964, 1971), Harker (1984, 1986a), and Yang et al. (2002). This approach has been applied numerously in various fields, e.g. the international wheat trade (Kolstad and Burris, 1986), natural gas market analysis (Zhuang and Gabriel, 2008 and Holz et al., 2008), or electricity markets (Hobbs, 2001 and Bushnell, 2003).

The Stackelberg model (section 2.3.3) deals with sequential move games (see Tirole (1988) for some examples) in which one player, the leader, maximises his profits given a set of complementarity conditions. Such problems are typically called Mathematical Programmes with Equilibrium Constraints (MPEC's) in the literature (e.g. Harker and Pang, 1988 or Luo et al., 1996).

The MPEC class of problems has been used for applications in various fields of research e.g. tax credits and biofuel production (Bard et al., 2000), non-competitive behaviour in markets for NO_x allowances and electricity (Chen et al., 2006), or the role

[11] Generally, the models presented here are particularly well-suited to scrutinise such spatial markets where the focus is on variable costs and not so much on fixed (e.g. investment) costs. Typically, the supply costs of resources and minerals produced by mining and quarrying industries (e.g. coal, iron ore, bauxite, manganese, copper ore, rare earth elements) have a much larger variable cost and smaller fixed cost component than for instance (conventional) natural gas and oil production. In markets that are characterised by a larger share of (constant) variable costs, or more precisely marginal costs, the short-run supply rationale of equating marginal costs to marginal revenues appears to be a better predictor for prices.

of dominant utilities in the European power system (Gabriel and Leuthold, 2010) to name but a few.

In all three models coal exporters control one or several export assets and coal importers (steel mills, coke producers, etc.) are assigned to importing regions. It is assumed that the exporters' objective is to maximise their respective profits. In the Stackelberg and the Cournot cartel scenarios the Big-Four control their mines as one player. In the Cournot oligopoly and the perfect competition scenario each of the four multinationals control their respective mines. In all the scenarios, players other than the Big-Four are modelled as national oligopolists. This assumption is typical for this strand of research and unproblematic in the presented paper as there is only one dominant player exporting metallurgical coal per country. Importers are assumed to behave as price takers.[12] Coal is traded via dry bulk vessel shipping routes.

The model consists of a network $NW(N, A)$, where N is a set of nodes and A is a set of arcs between the nodes. The set of nodes N can be divided into two subsets, $N \equiv M \cup J$, where $m \in M$ is an export mine and $j \in J$ is an import node. Players $i \in I$ control coal mines $m \in M_i$. A mine can only be controlled by one player. Mining costs (includes washing/upgrading), loading and inland transport costs, as well as port handling fees add up to a specific mine's constant FOB (Free On Board) costs c_m per produced unit of coal $x_{m,j}$. Seaborne transport costs amount to $\tau_{m,j}$ per unit $x_{m,j}$ shipped. For simplicity $\tau_{m,j}$ is the same for all mines $m \in M_i$ controlled by player $i \in I$.[13] In all three models, import demand in region $j \in J$ is represented by a linear function of the form:

$$p_j = P_j\left(\sum_{m\in M} x_{m,j}\right) = a_j - b_j \cdot \sum_{m\in M} x_{m,j} \tag{2.1}$$

where p_j denotes the price in region j as a function $P_j(.)$ of the imported quantity $\sum_{m\in M} x_{m,j}$. The parameter a_j denotes the reservation price, and parameter b_j specifies the slope of the demand function.

2.3.1 Cournot-Nash Model

In the Cournot-Nash model, the producers choose their optimal export quantity simultaneously. The amount of coal supplied by player $i \in I$ to region $j \in J$ is defined as $X_{i,j} = \sum_{m\in M_i} x_{m,j}$; let me define $X_{-i,j}$ as the quantity supplied by all other producers to region $j \in J$:

$$X_{-i,j} = \sum_{m\in M\neq M_i} x_{m,j} \tag{2.2}$$

[12] Although historically this assumption is debatable, recent research by Bowden (2012) has pointed out the erosion of buyer-side market power since the early 2000s.

[13] This simplification is unproblematic as the exporters' mines are typically clustered in one region and hence their coal is exported through the same port.

Player i's profit maximisation problem Ω_i consists of the profit function (2.3) and the constraints (2.4) and (2.5):

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(X_{-i,j} + X_{i,j} \right) \cdot x_{i,j} - \tau_{m,j} \cdot x_{m,j} - c_m \cdot x_{m,j} \right] \tag{2.3}$$

subject to:

$$Cap_m \geq \sum_{j \in J} x_{m,j} \quad (\mu_m) \tag{2.4}$$

$$x_{m,j} \geq 0 \tag{2.5}$$

Restriction (2.4) ensures that production in mine $m \in M_i$ does not exceed the available mining capacity Cap_m in this mine. The strictly quasi-concave objective function (2.3) and the convex restrictions (2.4) and (2.5) form an optimisation problem, which has a unique solution. The first-order optimality conditions are thus necessary and sufficient for deriving a unique optimum if the set of feasible solutions is non-empty. The equilibrium conditions (KKT conditions) are derived using the first order derivatives of the Lagrangian of Ω_i. The Lagrangian multiplier μ_m is the shadow price of mining capacity of mine $m \in M_i$ controlled by player $i \in I$. It represents the value of a marginal unit of mining capacity, i.e. the increment of profits if the producer had an infinitesimally small unit of additional capacity. The FOCs correspond to the following complementarity conditions:

$$\tau_{m,j} + c_m + \mu_m + b_j \cdot x_{m,j} - [a_j - b_j \cdot (X_{-i,j} + X_{i,j})] \geq 0 \perp x_{m,j} \geq 0 \tag{2.6}$$

$$-\sum_{j \in J} x_{m,j} + Cap_m \geq 0 \perp \mu_m \geq 0 \tag{2.7}$$

Equation (2.1), constraint (2.5) and the first order conditions (2.6) and (2.7) for all players $i \in I$ together constitute the optimisation problem. The unique solution for this set of inequalities yields the equilibrium for this market. This mixed complementary problem is implemented using the software GAMS and solved with PATH.[14]

2.3.2 Perfect Competition

In the competitive model, the players face a similar optimisation problem as in the Cournot-Nash model, given by (2.3), (2.4) and (2.5), with the exception that the players cannot influence the market price in region $j \in J$. This leads to the following objective

[14]See Rutherford (1994) or Ferris and Munson (1998) for detailed information on complementarity programming in GAMS.

function for competitive players:

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(\sum_{m \in M} x_{m,j} \right) \cdot x_{m,j} - \tau_{m,j} \cdot x_{m,j} - c_m \cdot x_{m,j} \right] \tag{2.8}$$

Given the non-negativity of output condition and constrained production capacity, player i's profit maximisation problem Θ_i consists of profit function (2.8) and constraints (2.4) and (2.5).

The term $b_j \cdot x_{m,j}$ in (6) represents the oligopolistic mark-up on the market price in $j \in J$. However, in the perfect competition model, none of the players $i \in I$ has the ability to influence the market price in import region $j \in J$ by strategically choosing the amount of coal supplied. Therefore, the FOC (2.6) simplifies to (2.9) under the assumption of a linear demand function.

$$\tau_{m,j} + c_m + \mu_m - \left(a_j - b_j \cdot \sum_{m \in M} x_{m,j} \right) \geq 0 \perp x_{m,j} \geq 0 \tag{2.9}$$

FOC (2.9) states that $i \in I$ will supply coal to region $j \in J$ until the marginal costs of supply (i.e. transport costs plus the shadow price of capacity plus marginal FOB costs) equal the price in this region. FOCs (2.7) and (2.9) as well as equation (2.1) and constraint (2.5) constitute an optimisation problem with a unique solution (see section 2.3.1) which is implemented in GAMS and solved with PATH. Furthermore, the outcome of the model presented here corresponds to the outcome of a least-cost allocation determined by a benevolent social planner.

2.3.3 Stackelberg Model

The interaction between a leading player (leader) and the following players (followers) can be interpreted as a sequential move game with two periods in which the leader (irrevocably) decides in the first period how much to sell in the second period, taking into account the followers' best response in the second period to his decision. In the second period the followers engage in a Cournot-Nash game given the leaders' fixed output. It is assumed that the leader can commit to his decision taken in period one. The market is cleared in period two. Such problems can be modeled as an MPEC (see e.g. Dirkse and Ferris, 1999) where the leader maximises his profit given a set of the followers' optimality conditions, formulated as complementarity conditions (profit and capacity constraints).

In the Stackelberg setup, leader S controls the mines $m \in M_s$ which have individual FOB costs specified by κ_m.[15] The leader incurs seaborne freight costs f_j for coal

[15] The leader's production and transport costs are renamed for the sake of simplicity but rely on the same data as above.

shipments to import region $j \in J$. The leader's production in mine $m \in M_s$ is denoted by $q_{m,j}$ whereas $Q_j = \sum_{m \in M_s} q_{m,j}$ denotes the leader's total production. The followers $i \in I$ export coal $X_{i,j} = \sum_{m \in M_i} x_{m,j}$ to $j \in J$ which they produce in their respective mines $m \in M_i$. Let me define $Y_j = \sum_{i \in I} X_{i,j}$ as the sum of all followers' exports to $j \in J$.

The leader's profits are characterised by (2.10) whereas (2.11) is the mining capacity restriction and (2.12) states, that only positive output is possible.

$$max_{m \in M_s} \sum_{j \in J} [P_j (Q_j + Y_j) \cdot q_{m,j} - f_j \cdot q_{m,j} - \kappa_m \cdot q_{m,j}] \tag{2.10}$$

$$Cap_m \geq \sum_{j \in J} q_{m,j} \tag{2.11}$$

$$q_{m,j} \geq 0 \tag{2.12}$$

As the leader's profits depend on the output of the followers, Y_j, the leader also has to take into account the followers' best response to his decision. The followers essentially face the same optimisation problem as in the Cournot-Nash model which is given by (2.3), (2.4), and (2.5). However, in the Stackelberg model an individual follower's profit not only depends on his output $X_{i,j}$ and the other followers' output $X_{-i,j}$ (see definition (2.2)) but also on the leader's output decision Q_j. This leads to the following best-response function (2.13) in its complementarity form:

$$\tau_{m,j} + c_m + \mu_m + b_j \cdot x_{m,j} - [a_j - b_j \cdot (X_{-i,j} + X_{i,j} + Q_j)] \geq 0 \perp x_{m,j} \geq 0 \tag{2.13}$$

The upper-level optimisation problem (2.10) to (2.12) and the lower-level optimality conditions for all followers $i \in I$ (2.7) and (2.13) as well as inequality (2.5) and equation (2.1) together constitute the MPEC which is implemented in GAMS and solved with CONOPT using the GAMS convert tool for MPECs (see Ferris et al., 2002).[16]

2.4 Dataset

2.4.1 Supply Side Data

The supply side of the coking coal market is represented by a dataset comprising mining costs, inland transport costs, port handling costs, and seaborne freight rates between exporting and importing regions. The data used are on a mine-by-mine basis (about 100 export operations) for the years 2008, 2009, and 2010. The dataset covers dedicated export mines and mines that serve both international and domestic markets. The latter

[16]See appendix A for additional information on solution of the Stackelberg model and for the outline of a test model for ex-post optimal follower behaviour.

type of mines is particularly relevant for the USA and to some degree for Russia as well. The data stems from various sources such as company presentations (e.g. CoAL, 2009), annual reports, investment reports, business plans, market reviews (e.g. IEA, 2011b,c), research projects (e.g. Franke, 2011), articles written by industry experts (e.g. Rademacher, 2008; Bayer et al., 2009; Rademacher and Braun, 2011), expert interviews, etc. Mining cost changes were accounted for using the mining cost index published by the Australian Bureau of Statistics (see ABS, 2006 for details) according to the share of underground and open-cast mines in the dataset. For the United States and Canada mining costs were escalated based on the cost structure of the mines (share of the costs of inputs such as fuel, steel, explosives, labour, tyres, etc. on total costs) using input price data from the U.S. Bureau of Labour Statistics (BLS, 2011; see also Trüby and Paulus, 2012; Paulus and Trüby, 2011; and IEA, 2011b). Figure 2.1 presents the supply cost curve example (FOB) for the year 2008 for all players.

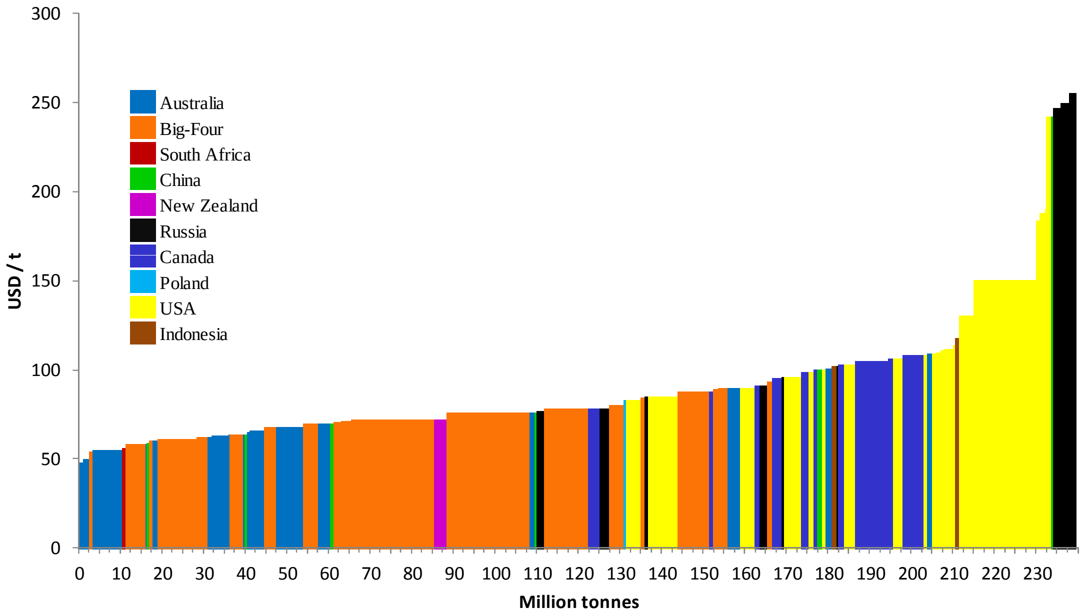

FIGURE 2.1: FOB supply cash costs of export mines as implemented in the models, 2008

Source: own analysis.

Maritime shipping costs $\tau_{m,j}$ between mines controlled by player $i \in I$ and importing regions $j \in J$ were calculated based on dry bulk freight rates data from McCloskey. Specifically, the freight rate data were regressed against shipping distances to determine the parameters $\gamma > 0$ and $0 < \varphi < 1$ of a freight cost function of the form $W(d_{m,j}) = \tau_{m,j} = \gamma \cdot d^{\varphi}{}_{m,j}$ where $d_{m,j}$ denotes the distance between m and j. The individual transport cost functions were calculated for every year. These cost functions are used in the model to determine consistent freight rates for every possible shipping route.

2.4.2 Demand Side Data

As described in section three, the inverse import demand function for metallurgical coal is assumed to be linear. Such a function can be characterized by a reference price and a reference quantity, i.e. real market outcomes in each year and a point elasticity parameter *eta*. Coking coal benchmark prices plus average freight costs were used as import reference prices and the actual import volumes of each importing region were used as reference quantity (table 2.2). The elasticity parameter determines the slope of the function in the reference point. Clearly, the elasticity is the most critical parameter in the demand representation. It is likely that the elasticity varies over time e.g. due to the dynamics of downstream steel markets. For reasons of limited data availability an estimation of the price elasticity of demand is not in the scope of the presented paper. Yet, to take into account the fact that the elasticity parameter is one of the key drivers of the model results, I test for a bandwidth of elasticity assumptions ranging from -0.1 to -0.8. Previous analyses have pointed out that coking coal demand is inelastic to price changes, i.e. $eta < 1$. Ball and Loncar (1991) estimate the price elasticity of coking coal demand to fall into a range of -0.3 to -0.5 in Western Europe and -0.15 to -0.4 in Japan. The authors however suggest that the price elasticity of demand is likely to increase in the future with market penetration of the PCI technology. Graham et al. (1999) consider an elasticity value of -0.3 to be most likely to have prevailed in this market in the year they analysed i.e. 1996.

TABLE 2.2: Reference import demand quantities in million tonnes

	Europe and Mediterranean	*Japan*	*Korea*	*Chinese Taipei*	*China*	*India*	*Brazil*	*Other Latin America*	*Other/ Unspecified*	Total
2008	63	64	16	8	3	26	11	4	18	213
2009	43	51	20	4	22	26	12	3	10	191
2010	58	60	27	8	34	35	13	4	7	245

Source: IEA (2011a).

2.5 Statistical Measures

Analysing actual and predicted trade flows between exporting and importing regions is one way to assess the accuracy of a model. In doing so, I apply several statistical measures: Theil's inequality coefficient, a linear hypothesis test, and Spearman's rank correlation coefficient. These are standard procedures for testing prediction accuracy of this model class (e.g. Kolstad and Abbey, 1984; Kolstad and Burris, 1986; Graham et al., 1999; Bushnell et al., 2008). For consistency reasons and as there is no data on company-level trade-flows available, all actual trade-flows are on a national level and stem from IEA (2011a). Firstly, Theil's inequality coefficient U is used to gain insights into the differences between predicted and actual values (Theil, 1961). The set $k \in K$

denotes trade flow pairs between importing regions $j \in J$ and exporting regions $i \in I$ (section 3.3).[17] The inequality coefficient is basically the root-mean-squared error of the model-based trade flows X_k and the corresponding actual A_k trade flows:

$$U = \frac{\sqrt{\sum_{k \in K}(X_k - A_k)^2}}{(\sqrt{\sum_{k \in K} {X^2}_k} + \sqrt{\sum_{k \in K} {A^2}_k})} \tag{2.14}$$

As can be seen in (2.14), I use the scaled version of U in which the coefficient lies between 0 and 1. An inequality coefficient of 0 indicates that the predicted values are equal to the actual values whereas a coefficient close to 1 suggests that there is a large spread between predicted and actual values. Therefore lower values (in a relative sense) are considered a better indicator for model accuracy. Hypothesis testing is not possible as Theil's inequality coefficient is distribution-free. Additional information can be gained from a decomposition of U into its covariance proportion U_{COV} (2.16), its variance proportion U_{VAR} (2.17), and its bias proportion U_{BIAS} (2.18) using the mean-squared-error MSE (2.15).

$$MSE = \sum_{k \in K}(X_k - A_k)^2 + (\sigma_X - \sigma_A)^2 + 2 \cdot (1 - r_{XA}) \cdot \sigma_X \cdot \sigma_A \tag{2.15}$$

$$U_{COV} = 2 \cdot (1 - r_{XA}) \cdot \sigma_X \cdot \sigma_A / MSE \tag{2.16}$$

$$U_{VAR} = (\sigma_X - \sigma_A)^2 / MSE \tag{2.17}$$

$$U_{BIAS} = \sum_{k \in K}(X_k - A_k)^2 / MSE \tag{2.18}$$

The standard deviation is denoted by σ whereas r is the correlation coefficient. The subscript A denotes actual trade-flows data and the subscript X denotes predicted trade-flows data. The covariance proportion measures the spread of data points along a 45° line that would result if the trade values of a perfect prediction model were plotted against actual trade values (Kolstad and Abbey, 1984). The covariance proportion measures the degree to which a regression line through the scatter plot of actual versus predicted trade-flows deviates from 1 (i.e. the slope that would result if the predicted values were equal to actual values). As suggested by Kolstad and Abbey (1984) and Kolstad and Burris (1986), I interpret a large value of the covariance proportion as an indicator for a good model as one would expect some random component in model predictions.

Following Bushnell et al. (2008), a more formal test can examine whether the values of the predicted trade flow matrix are meaningfully different from the values of the actual matrix. Although the arrangement in this analysis is different from Bushnell et al. (2008) the basic idea of employing a linear hypothesis test for model validation remains the same. The empirical model is that actual trade-flows equal predicted trade-flows. In my case, this can be done by regressing actual trade-flows A_k on the predicted

[17] There are 45 observations (trade-flows) per year, per elasticity assumption, and per model.

trade flows X_k:

$$A_k = \beta_0 + \beta_1 \cdot X_k + \epsilon_k \tag{2.19}$$

I estimate equation (2.19) using ordinary least squares (OLS). In order for the respective model's trade-flows to be consistent with the actual values, I require that $\beta_0 = 0$ and $\beta_1 = 1$ cannot be rejected on typical significance levels. Finally, I employ Spearman's rank correlation coefficient (Spearman's *rho*) to analyse the correlation of the market shares of exporters in importing regions. The ranking of trade-flows according to volume corresponds to a ranking of the market shares of exporters in importing regions. Spearman's *rho* is generally expressed as

$$rho = 1 - \sum_k d_k^2/(n^3 - n) \tag{2.20}$$

where d_k is the difference in the ranks of the predicted and the actual trade-flows and n is the sample size. A large value of Spearman's *rho* (one at maximum) indicates a good reproduction of the market shares (ranking of the trade-flows) in the model. However, just looking at *rho* can be misleading. Consider two equal trade flow matrices. They would deliver a *rho* of one. Now divide one of the matrices by two. The ranking of the trade flows would remain the same although one market is twice as large as the other.

2.6 Results

2.6.1 Trade-flows

The accuracy of predicted trade-flows is a key indicator for the quality of a spatial market model. Actual and predicted trade-flows of all market structure scenarios for all years and elasticities were analysed with the statistical measures described in section 5.[18] With regard to Theil's inequality coefficient and its covariance proportion, two observations stand out (figure 2.2): first, the Stackelberg model performs best for all elasticities and years. However, the coefficients for the Stackelberg and Cournot oligopoly models converge with increasing price sensitivity and produce virtually the same results for higher elasticities i.e. $eta < -0.2$ (except for 2009). Second, the perfect competition model performs better than the Cournot cartel model for lower elasticities whereas the Cournot cartel scenario performs better for higher elasticities. Yet, both models appear to be relatively poor predictors for trade-flows, as they typically exhibit markedly higher inequality coefficients than the Stackelberg and Cournot oligopoly models.

[18] All trade-flow matrices can be found in appendix A.

TABLE 2.3: Results of the linear hypothesis test

	Stackelberg			Cournot cartel			Cournot oligopoly			Perfect competition		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
$eta = -0.1$	0.908	0.614	0.767	0.011*	0.002**	0.002**	0.178	0.034*	0.075.	0.000***	0.000***	0.000***
$eta = -0.2$	0.929	0.832	0.903	0.033*	0.003**	0.007**	0.503	0.075.	0.262	0.000***	0.000***	0.000***
$eta = -0.3$	0.685	0.665	0.880	0.098	0.006**	0.022*	0.872	0.158	0.655	0.000***	0.000***	0.000***
$eta = -0.4$	0.657	0.926	0.967	0.265	0.009**	0.096	0.981	0.277	0.863	0.000***	0.000***	0.000***
$eta = -0.5$	0.559	0.823	0.986	0.560	0.015*	0.283	0.733	0.436	0.995	0.000***	0.000***	0.000***
$eta = -0.6$	0.490	0.902	0.981	0.872	0.025*	0.545	0.455	0.589	0.971	0.000***	0.000***	0.000***
$eta = -0.7$	0.395	0.790	0.949	0.920	0.043*	0.731	0.365	0.787	0.940	0.000***	0.000***	0.000***
$eta = -0.8$	0.348	0.748	0.895	0.678	0.077.	0.949	0.320	0.947	0.884	0.000***	0.000***	0.000***

Source: own calculations. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '. .

The analysis of Spearman's *rho* supports the above findings (figure 2.2). Clearly, all non-competitive models perform substantially better than the perfect competition model. This result is robust for all years and all elasticity cases. Among the non-competitive models the Stackelberg and Cournot oligopoly models generally perform slightly better than the Cournot cartel model.

The results of the linear hypothesis test confirm these findings (table 2.3). The hypothesis that the perfect competition model predicts trade can generally be rejected on the 99.9% level, irrespective of the year and the elasticity. The Cournot cartel scenario can generally be rejected on typical significance levels for high elasticities in 2008 and 2010 and for all elasticities in 2009. The Cournot oligopoly scenario can be rejected only in 2009 for $eta = -0.1$ and $eta = -0.2$ and in 2010 for $eta = -0.1$. Linear hypothesis testing does not suggest rejecting the hypothesis that the Stackelberg model actually predicts trade for any of the elasticities or years analysed.

With regard to accuracy of trade-flows, the oligopolistic models typically perform better than the competitive model due to a higher diversification of trade. This higher trade diversification in the non-competitive models stems from the players' profit maximisation: an oligopolist exports to a certain importing region until his marginal revenue equals marginal costs there. With a high market share in a certain importing region, perceived marginal revenue for the exporter is low, hence making it attractive to diversify the export structure. This rationale may cause trade with regions that would not occur for cost reasons in a perfectly competitive market.

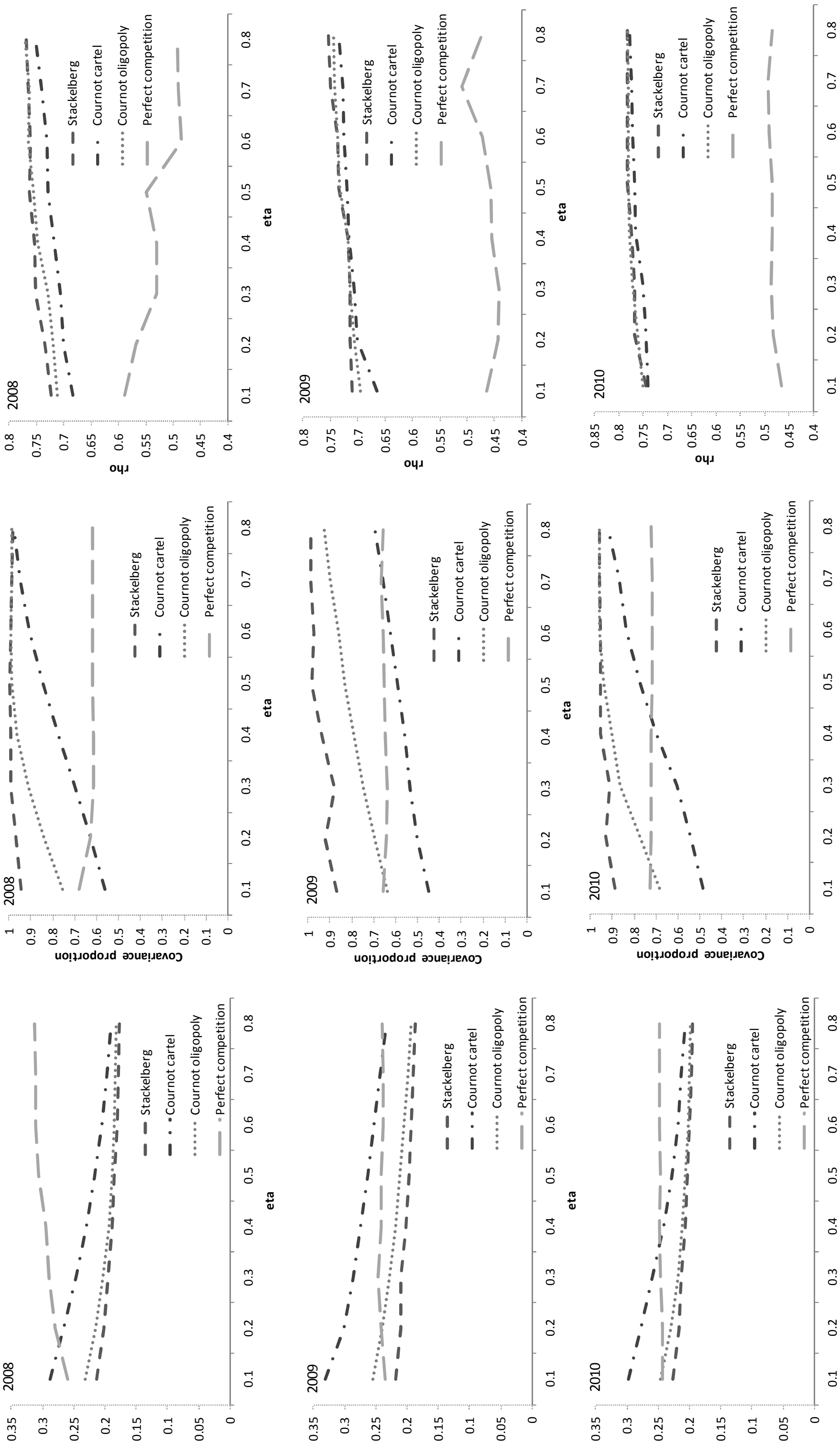

FIGURE 2.2: Theil's inequality coefficient and the covariance proportion as well as Spearman's *rho* as functions of *eta*

Source: own calculations.

2.6.2 Prices

As a second indicator for model prediction accuracy I compare coking coal benchmark prices to corresponding coal prices from the four market structure scenarios (figure 2.3).[19] The first finding is that the perfectly competitive model systematically underestimates real market prices irrespective of the elasticity parameter and the year. The second finding is that the non-competitive models can explain real market prices for a range of elasticities. The Stackelberg model can reproduce prices in 2008 for $eta = -0.2$ to $eta = -0.4$, in 2009 for $eta = -0.5$ to $eta = -0.8$ and in 2010 for $eta = -0.4$ to $eta = -0.6$. The Cournot oligopoly model can reproduce prices for slightly higher elasticity parameters, specifically in 2008 for $eta = -0.3$ to $eta = -0.4$, in 2009 for $eta = -0.6$ to $eta = -0.8$ and in 2010 for $eta = -0.5$ to $eta = -0.6$. The Cournot cartel model can reproduce prices only in 2008 and 2010 and requires the highest elasticity parameters to do so i.e. $eta = -0.5$ for 2008 and $eta = -0.6$ to $eta = -0.8$ for 2010.

[19] Although the analysis accounts for all metallurgical coal qualities (hard coking coals, semi-soft coking coals, and PCI coals), these coal-types are substitutes and compete in the same market. The relevant prices for comparison of model results and actual market outcomes are nevertheless hard coking coal benchmark prices. The reason for this is that the hard coking coal benchmark price is also the driver of semi-soft coking and PCI coals prices, with the latter two typically being a function of the hard coking coal benchmark price. Furthermore, hard coking coal trade volume is larger than semi-soft coking coal or PCI coals trade volumes.

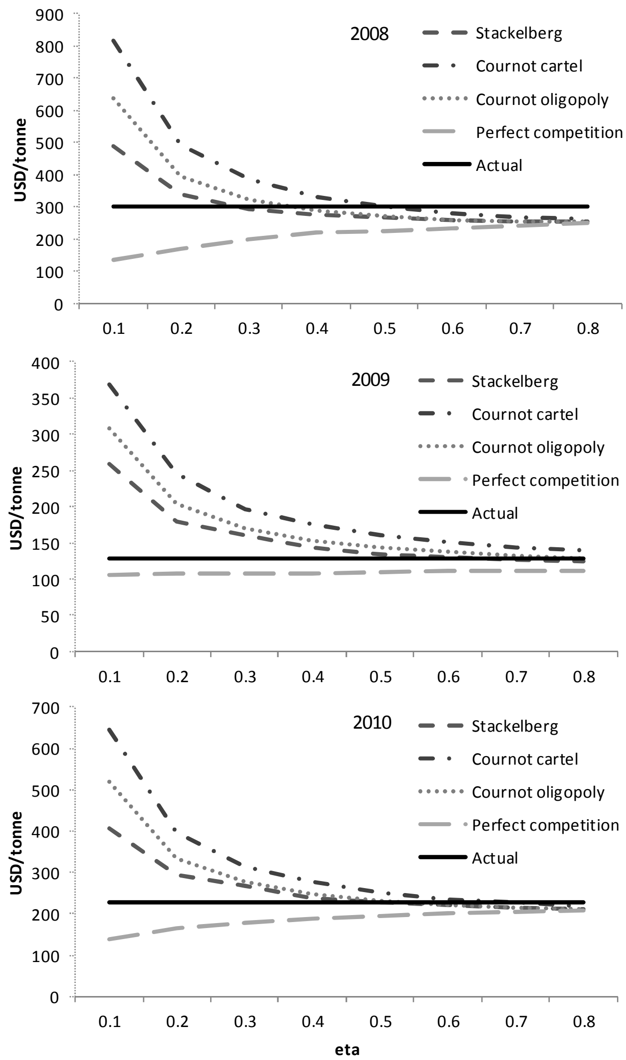

FIGURE 2.3: Model-based prices as a function of *eta* and real market benchmark price

Source: own calculations. Benchmark prices taken from ABARES and McCloskey.

2.6.3 Profits and Export Volumes

In terms of profits, the Big-Four can typically gain most in the Stackelberg model by colluding and benefitting from their first mover advantage (table 2.4). This becomes clearly visible when comparing the Big-Four's profits in the Stackelberg model with the corresponding profits in the Cournot cartel scenario. In the Stackelberg model the Big-Four export more than in the Cournot cartel scenario. This is detrimental to the other players – the followers – who reduce their exports. The market price is *c.p.* lower in the Stackelberg scenario than in the Cournot cartel scenario (figure 2.3) but the expansion in sales overcompensates this effect for the leader, rendering this strategy profitable.

Table 2.4: Aggregated profits (2008 to 2010) from metallurgical coal exports in billion USD

	Stackelberg	Cournot cartel	Cournot oligopoly	Perfect competition
$eta = -0.1$				
Big-Four	94.97	81.27	94.82	16.16
Others	91.32	207.47	143.19	15.47
$eta = -0.2$				
Big-Four	60.22	52.83	58.49	22.65
Others	61.07	115.06	81.32	23.93
$eta = -0.3$				
Big-Four	49.96	43.50	49.14	27.10
Others	53.80	83.54	62.14	29.78
$eta = -0.4$				
Big-Four	45.15	40.03	44.62	30.32
Others	47.78	68.88	52.94	34.08
$eta = -0.5$				
Big-Four	42.54	38.13	42.03	31.81
Others	45.03	59.82	47.64	36.06
$eta = -0.6$				
Big-Four	40.53	37.30	40.45	33.39
Others	43.93	53.74	44.81	38.12
$eta = -0.7$				
Big-Four	39.13	37.33	39.07	34.60
Others	43.03	50.31	43.74	39.81
$eta = -0.8$				
Big-Four	38.51	37.80	38.50	35.69
Others	42.90	47.51	43.41	41.30

Source: own calculations.

However, in the Stackelberg scenario the Big-Four's profits are only marginally higher than the sum of the individual four multinationals' profits in the Cournot oligopoly scenario. These two models are based on different market structure assumptions but produce similar results in terms of trade-flows, prices, and profits: compared to the Cournot oligopoly scenario there are fewer players in the Stackelberg model since the Big-Four act as one single player. In absence of a first mover advantage, this would typically imply a reduction of exports by the Big-Four (table 2.5) and an expansion of exports by the other players (compare Cournot oligopoly with Cournot cartel). However, the strategic effect of the first-mover advantage implies that the Big-Four, as a Stackelberg leader, export more whereas the other players reduce their output. Hence, the strategic effect of the first mover advantage partially compensates the effect of higher market concentration leading to similar results of the two models. This outcome is amplified by the fact that for higher elasticities and for the years 2008 and 2010 the Big-Four do not have sufficient export capacity to fully benefit from their first-mover advantage. In these two years, the Big-Four produce close to their capacity limit in the Cournot oligopoly scenario. For higher elasticities they would want to export more in the Stackelberg

Table 2.5: Exports in million tonnes

	Stackelberg			Cournot cartel			Cournot oligopoly			Perfect competition		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
$eta = -0.1$												
Big-Four	**99.6**	89.9	**111.4**	48.4	39.3	56.9	72.5	66.7	84.2	**99.6**	**99.6**	**111.4**
Others	101.4	83.5	115.9	131.1	119.6	146.3	118.6	100.2	131.7	124.3	94.4	142.9
$eta = -0.2$												
Big-Four	97.2	92.6	**111.4**	54.7	46.2	64.0	77.8	70.0	90.7	**99.6**	**99.6**	**111.4**
Others	110.6	84.7	120.2	132.7	113.0	147.0	122.5	100.3	133.1	130.6	97.0	146.4
$eta = -0.3$												
Big-Four	98.9	87.6	105.3	61.1	49.9	71.0	84.4	73.5	99.3	**99.6**	**99.6**	**111.4**
Others	114.9	90.4	127.5	134.3	113.0	147.8	123.2	100.2	130.5	132.9	99.8	149.2
$eta = -0.4$												
Big-Four	98.4	93.3	**111.4**	67.5	52.7	79.1	91.2	77.1	103.4	**99.6**	**99.6**	**111.4**
Others	119.6	88.9	128.7	135.8	112.5	145.8	123.3	99.7	132.8	134.6	102.7	149.2
$eta = -0.5$												
Big-Four	**99.6**	**99.6**	**111.4**	73.5	56.3	86.4	96.2	80.4	108.2	**99.6**	**99.6**	**111.4**
Others	122.6	87.1	133.0	137.6	112.1	145.5	124.9	99.6	134.6	137.8	104.5	149.7
$eta = -0.6$												
Big-Four	**99.6**	96.0	**111.4**	80.2	60.0	92.5	**99.6**	83.0	**111.4**	**99.6**	**99.6**	**111.4**
Others	127.3	92.2	137.3	138.2	111.4	146.7	127.3	99.8	137.3	139.4	106.0	149.7
$eta = -0.7$												
Big-Four	**99.6**	98.4	**111.4**	86.4	63.8	96.6	**99.6**	86.2	**111.4**	**99.6**	**99.6**	**111.4**
Others	132.1	92.8	141.5	138.0	110.7	146.9	132.1	100.0	141.5	**140.0**	108.4	149.7
$eta = -0.8$												
Big-Four	**99.6**	99.2	**111.4**	92.6	67.3	103.4	**99.6**	89.5	**111.4**	**99.6**	**99.6**	**111.4**
Others	134.6	94.4	145.8	136.8	110.3	146.9	134.6	99.9	145.8	**140.0**	110.3	149.7

Source: own calculations. Bold case indicates binding capacity constraint.

scenario, yet short of capacity they are constrained to the corresponding Cournot output (table 2.5).

Another interesting result is that in the Cournot cartel scenario collusion is detrimental to the profits of the Big-Four. In a basic Cournot model it is unclear if partial cartelisation (or a merger) leads to higher profits for the colluding players (Salant et al., 1983). Whether collusion is profitable depends on the number of players inside and outside the cartel and the amount of spare capacity held by the outsiders. In the international metallurgical coal trade, the players outside the assumed cartel have sufficient spare capacity to expand their exports and thus the Big-Four cannot increase their profits through collusion.

2.7 Discussion of results

When interpreting the results of the model runs, one has to keep in mind two aspects: first, the elasticity of demand is a key unknown in this analysis but at the same time a major driver for the results. Therefore, I presented results for a large bandwidth of elasticities. For the sake of simplicity I chose single digit equidistant elasticity points. However, in reality the elasticity is neither a single digit parameter nor a constant over time and geography. Second, there is some inevitable noise in the data used to compute the model runs as well as in the real market trade-flow data used to assess prediction accuracy. Hence, the goal of the analysis cannot be to exactly reproduce market equilibria but to analyse whether a specific market structure systematically and robustly performs better than another.

In this respect, the main findings of the presented paper are threefold: Firstly, perfect competition cannot explain market equilibria in the metallurgical coal trade in the period 2008 to 2010. The statistical measures suggest that the competitive model predicts trade-flows poorly and in most cases markedly worse than the non-competitive models. Moreover, the competitive model systematically underestimates prices. Often it is argued that prices exceeding marginal costs are not due to market power exertion but due to capacity scarcity leading to demand rationing. Indeed, in a market without a spatial structure it might be very difficult to detect strategic behaviour if capacity scarcity is also an issue. In a spatial market a competitive model would however still produce the least-cost trade matrix even if capacity was scarce leading to a low degree of trade diversification. Consequently, given the weak performance of competitive models with regard to trade-flow reproduction and the fact that the supply capacity data suggests sufficient capacity availability, the argument of scarce capacity forcing up prices is implausible in this market.

Secondly, non-competitive models, specifically the Cournot oligopoly and Stackelberg models, reproduce trade-flows and prices accurately for mid-range elasticities. These elasticity ranges are in line with the results of previous studies on coking coal demand elasticities. Interestingly, these two models lead to very similar results in terms of trade-flows, prices, and profits. This implies that, under the given set of assumptions, the Big-Four could hardly benefit from a potential first mover advantage even if they would determine their exports cooperatively. The poor performance of the competitive model and the comparably good performance of the non-competitive models suggest that the metallurgical coal trade was subject to strategic behaviour in the period 2008 to 2010.

Finally, under the given set of assumptions, cartelisation between the Big-Four is unattractive. In the Cournot cartel scenario collusive behaviour is detrimental to the total profits of the four multinationals. Although cartelisation combined with a first-mover advantage was shown to be by and large a profitable strategy, the profit increment in the Stackelberg model was marginal when compared to the Cournot oligopoly scenario. Hence, the incentive to collude is small for the Big-Four. Moreover, the performance of the Cournot cartel model with regard to trade-flow prediction accuracy and price reproduction is mediocre, especially in 2009.

2.8 Conclusions

Three optimisation models for typical resource markets were developed in the presented paper and applied to the international metallurgical coal market, from 2008 to 2010, based on a detailed dataset representing the supply side characteristics of the market.

The demand side price responsiveness was accounted for by computing model runs for a large bandwidth of elasticities. Predicted trade-flows were analysed using statistical measures and model-based prices were compared to actual market prices.

The numerical results suggest that market equilibria in the seaborne metallurgical coal market cannot be explained by perfectly competitive conduct. However, two non-competitive models reproduced market outcomes reasonably well. Specifically, a Stackelberg model, in which the Big-Four act as a cooperative leadership cartel and a Cournot oligopoly model in which the members of the Big-Four compete individually with other players in the market were employed. Both models produced similarly convincing results for slightly different, but in any case realistic, ranges of elasticities. Hence, which of the two models is indeed the better predictor depends essentially on a high resolution estimation of the temporal and regional price elasticity of demand. Yet, for want of hard evidence of a first mover advantage and in light of the small incentive to collude in this market, the Cournot oligopoly scenario has a strong qualitative backing.

Strategic behaviour in metallurgical coal markets should be taken seriously due to the importance of this coal variety in steel-making and the crucial role of steel in global economic activity. Vertical integration could be a promising strategy for steel mills to reduce their exposure to the oligopolistic pricing. Although detrimental to welfare, pooling demand could – as in the past – be another viable strategy to reduce supply side market power.

Based on the insights of the presented paper, modelling other forms of sequential strategic interaction in metallurgical coal markets could be worthwhile. Although currently computationally challenging, an example for this could be a two-stage game with a leader-group of firms engaging in Cournot competition in the first stage and taking into account the reaction of a follower-group of firms engaging in Cournot competition in the second stage.

Chapter 3

Market Structure Scenarios in International Steam Coal Trade

3.1 Introduction

Behind oil but ahead of natural gas, coal is the second-most important primary energy source. It is mainly used for electricity and heat generation. About 36% of the global electricity generation is based on hard coal[20]. Although most of the coal is produced and consumed domestically, international steam coal trade is on the rise[21]. Price volatility has increased too, and the years 2007 and 2008 both saw unprecedented price spikes. Steam coal prices in North Western Europe reached a maximum of 210 USD/t in mid-2008 and averaged 147 USD/t for the whole year; this is more than 130% above the average price of 64 USD/t in 2006.[22] Prices decreased with the fall of the financial crisis in the second half of 2008 but remained relatively high throughout 2009 and 2010.[23]

The price increases on the spot markets for internationally traded coal in recent years were paralleled by significant structural changes on the demand and the supply sides. During the last decade total trade volume grew by more than 60% between 2000 and 2009 on the seaborne market. This development is mainly caused by a strong growth of energy demand in Asian economies. Recently, India and South East Asian economies have become major importers in the Pacific market. Moreover, China, a major net exporter at the beginning of the last decade has drastically increased imports since 2005.

[20] See IEA (2010b). Data for 2008.

[21] The classification of hard coal (distinct from lignite) comprises steam coal and coking coal. Steam coal (or thermal coal) is mainly used in electricity generation whereas coking coal is used for metallurgical purposes.

[22] See Ritschel (2009a).

[23] The Asian marker (North Western European marker) was 79 USD/t (70 USD/t) in 2009 and 105 USD/t (92 USD/t) in 2010.

The supply side is dominated by countries with mainly export-oriented mining industries like South Africa, Australia, Indonesia, and Colombia. The latter two countries are relatively new players in this market and have expanded their supply capacity quickly during the last decade. Moreover, in some countries, governments have developed national coal strategies during the last years, often tightening their control of coal exports, for instance in China or Indonesia[24]. Due to governmental control in some countries or the influence of large company consortia and industry associations in other countries, steam coal supply tends to be aggregated on a national level rather than on a firm level. In this context, the international steam coal trade market structure appears oligopolistic.

Given the growing importance of several new suppliers, the emergence of national energy and coal strategies in several countries and the dramatic recent steam coal price evolutions, we test whether market structures in 2006 and 2008 can be described either through competitive or oligopolistic conduct. To do so, we develop an optimisation model for computing spatial market equilibria in competitive and oligopolistic international trade markets. The equilibrium modelling approach was introduced by Samuelson (1952), with his work on the programming of competitive equilibria in spatial markets and generalised for various non-competitive market structure scenarios: e.g., by Takayama and Judge (1964, 1971), Harker (1984, 1986a) and Yang et al. (2002). The model is implemented as a mixed complementarity programme (MCP) with the software GAMS and based on a unique coal market dataset of EWI. This dataset comprises *inter alia* supply capacities and costs, including time-dependent supply cost functions based on input price evolutions to account for recent supply cost increases.

We find that actual prices in 2006 are in line with the competitive benchmark in Europe, but prices in Asian importing regions exceed marginal costs. In 2008, prices and volumes are not consistent with the competitive benchmark. Furthermore, trade flows are more diversified in the real market than in the competitive scenario. However, for both years, actual prices were lower than the oligopolistic prediction. Generally, the results indicate that competitive models are not able to fully reproduce coal market equilibria, particularly in 2008.

Literature on market conduct in international steam coal trade is relatively scarce. Abbey and Kolstad (1983) present a qualitative analysis of the potential to exert market power in steam coal trade. Kolstad and Abbey (1984) were the first to quantitatively analyse strategic behaviour in international steam coal trade in the early 1980s using an equilibrium model. In addition to perfect competition, they model various imperfect market structures. The authors find that a non-competitive market structure consisting of a duopoly and a monopsony effectively simulates the actual trade patterns. However,

[24] China constantly reduced export licences (from 80mt in 2005 to less than 20mt in 2011). Furthermore, the Chinese government started a programme to restructure and consolidate the coal mining industry (Peng, 2011). In Indonesia only Indonesian companies or consortia are eligible for mining concessions (Baruya, 2009).

since that time the steam coal trade market has changed substantially. We follow the approach of Kolstad and Abbey (1984) by using a partial equilibrium model and update their research with recent data. Haftendorn and Holz (2010) produced a paper most closely related to ours. They model a number of major seaborne coal trade routes and apply a mixed complementarity model to test if the trade volumes on these routes fit competitive or Cournot-Nash behaviour in the years 2005 and 2006. They conclude from their results that the steam coal trade market is better represented by perfect competition.

We add three important aspects to their analysis. First, while their research focuses on selected major trade routes, we extend the analysis to cover the full seaborne steam coal trade market[25]. Second, we use a different database and generalise the model for multi-production plant players to account for cost differences in mining regions and mining technologies. It is reassuring that, for 2006, in an independent approach we find qualitatively similar results to those of Haftendorn and Holz (2010). Third, and most important, by extending the time considered up to 2008, we are able to show that the actual market equilibrium deviated significantly from a perfectly competitive benchmark equilibrium.

The remainder of the presented paper is structured as follows: First, we will briefly outline the current situation on the seaborne steam coal trade market. Section 3.3 proceeds with a detailed description of the model and its properties. Then, in section 3.4 the supply and demand side data input is described. The scenario design is outlined in section 3.5. Section 3.6 presents the model results. Section 3.7 discusses results for 2008, and finally, section 3.8 concludes the presented paper.

3.2 The Seaborne Steam Coal Trade Market

The majority of steam coals are not traded internationally but are produced and consumed in domestic markets. In 2008 total global hard coal production reached 5850 mt.[26] The two largest domestic markets are China and the USA, together comprising more than 65% of total production. About 13% of the global steam coal production is traded internationally, and more than 90% of international steam coal trade is seaborne. In this submarket, two different types of suppliers interact with each other: countries that have a dedicated export-oriented mining industry and countries with chiefly inland-oriented

[25]The larger coverage might not only be an advantage in terms of higher completeness. Note that the omitted volumes in Haftendorn and Holz (2010) stem from smaller producers and are accounted for in our oligopoly model as part of the competitive fringe. This systematically leads to lower prices compared to just ignoring these quantities. Furthermore, a higher demand side coverage leads to a higher production of exporters that are modeled in both analyses. With an increasing marginal cost function, this systematically raises prices compared to ignoring these demand regions.

[26]See Ritschel (2009a); includes coking coal.

mining industries[27]. The former type primarily comprises South Africa, Colombia, Australia, and Indonesia and represents most of the supply capacity for the international trade market. These export industries usually have a cost advantage over domestic industries due to good coal qualities, low mining costs, and economical access to transport infrastructure. The latter type primarily consists of China, the USA, and Russia. These countries have some dedicated export collieries, but most of the potential *export* capacity can serve both the national and the international markets. Depending on the relation of export prices, to domestic prices these mines supply either domestic consumers or maritime trade markets (swing suppliers). The majority of domestic mines are always extramarginal to international markets due to low coal quality, contractual obligations, high supply costs, or lack of access to infrastructure.

The seaborne trade market can be divided into Pacific and Atlantic market regions[28]. Major importing regions in the Atlantic market are the USA and Europe (including neighbouring Mediterranean countries) with the United Kingdom and Germany at the top. Traditionally, these importing regions are primarily supplied by South Africa, Colombia and Russia.

The Pacific market has grown faster in recent years. High quantities are imported by Japan, South Korea, and Taiwan, all three of which have virtually no indigenous coal production and therefore rely heavily on imports. However, most of the growth has come from emerging import regions like India, South East Asia, and China. The supply side is dominated by Australia and Indonesia, although the sustained high prices in Asia have attracted increasing spot volumes from South Africa, and very recently, also from Colombia.

3.3 Model Description

We develop a spatial equilibrium model for the seaborne steam coal market in which exporters and importers trade with each other. Coal exporters control one or more coal-producing regions (including the infrastructure), and coal importers are assigned to demand regions. These players trade steam coal with each other via bulk carrier shipping routes. It is assumed that the exporters' objective is to maximise their respective profits. Importers are assumed to act as price takers[29]. The optimisation model is formulated as a mixed complementarity problem (MCP) by deriving the Karush-Kuhn-Tucker (KKT)

[27] See e.g. Kopal (2007) or Rademacher (2008).

[28] During the last decade trade flows between the two regions grew considerably and recent research has pointed out that the global steam coal market is well integrated (see e.g. Warell (2006) or Li (2008)). Nevertheless, we use these terms in the presented paper in a geographical sense to better structure our analysis.

[29] Since all coal flows are adjusted to a calorific value of 25.1 MJ/kg coal is a homogenous good for the importers. Importers are not able to influence market prices through strategic (oligopsonistic) market behaviour.

conditions. In equilibrium, the set of prices and quantities simultaneously satisfies all first-order-optimality conditions.

The model consists of a network $NW(N, A)$, where N is a set of nodes and A is a set of arcs between the nodes. The set of nodes N can be divided into two subsets, $N \equiv E \cup I$, where $i \in E$ is an export region and $j \in I$ is a demand node. Players $z \in Z$ control export regions $i \in E_z$. Export regions can only be controlled by one player, $\bigcap_{z \in Z} E_z \equiv \oslash$. The set of arcs $A \equiv E_z \times I$ consists of arcs $f_{(z,j)}$. Table 3.1 gives an overview of demand regions, export regions, and the corresponding players as modelled in the presented paper[30].

Table 3.1: Model regions

Exporting regions	*Corresponding players*	*Demand regions*
New South Wales/open cast	Australia	Europe (including Mediterranean)
New South Wales/underground	Australia	Japan
Queensland/open cast	Australia	South Korea
Queensland/underground	Australia	Taiwan
Mpumalanga/open cast	South Africa	China
Mpumalanga/underground	South Africa	India
Kalimantan & Sumatra	Indonesia	Latin America
Kuzbass & Donbass	Russia	North America
Eastern Kuzbass, Yakutia and far East	Russia	South East Asia
Colombia	Colombia	
Shanxi	China	
Central Appalachia	USA	
Venezuela	Venezuela	
Vietnam	Vietnam	
Poland	Poland	
Spitsbergen	Norway	

Mining costs, average inland transport costs, and port terminal costs add up to a quadratic free-on-board (FOB) supply function[31] depending on the produced quantity q_i per export node $S_i(q_i)$. Seaborne transport costs $\tau_{z,j}$ per unit $x_{z,j}$ shipped. However, the transport cost parameter $\tau_{z,j}(d_{z,j})$ depends on the distance $d_{z,j}$ between z and j. Individual transport cost functions were calculated for every year based on historical data[32]. Import demand is represented by a linear function of the form:

$$p_j \left(\sum_z x_{z,j} \right) = a_j - b_j \cdot \sum_z x_{z,j} \tag{3.1}$$

[30]The model export nodes cover about 98% of real market exports. The remaining 2% of exports is divided among the model regions according to their share of total production. Import side coverage is about 95%. The import balance is divided among the import regions according to their share of total imports.

[31]Quadratic marginal functions had the best fit when regressed against a dataset of mining costs. Furthermore, quadratic marginal cost functions capture important characteristics of steam coal supply e.g. an increasing increment of marginal costs the more capacity is utilised.

[32]Bulk carrier freight data were provided by McCloskey Coal Information, Frachtkontor Junge & Co., and Baltic Exchange. See section 3.4.2 for a detailed description of transport cost data.

where p_j denotes the price in region j subject to the imported quantity. The parameter a_j denotes the reservation price, and parameter b_j specifies the slope of the demand function. Production costs W_i in node $i \in E$ correspond to the integral under the quadratic FOB supply function:

$$W_i(q_i) = \int_0^{q_i} S_i(q)dq = \frac{1}{3} \cdot \alpha_j \cdot q_i^3 + \frac{1}{2} \cdot \beta_i \cdot q_i^2 + \rho_i \cdot q_i \tag{3.2}$$

The amount of coal supplied by player $z \in Z$ to region $j \in I$ is defined as $x_{z,j}$; let us define $\widetilde{x}_{z,j}$ as the quantity supplied by all other producers to region $j \in I$:

$$\widetilde{x}_{z,j} = \sum_{\substack{k \in Z \\ k \neq z}} x_{k,j} \tag{3.3}$$

Producer z's profit maximisation problem Ω_z consists of the objective function F_z and the constraints (3.5)-(3.7):

$$F_z = \sum_j p_j \left(\widetilde{x}_{z,j} + x_{z,j}\right) \cdot x_{z,j} - x_{z,j} \cdot \tau_{z,j} - W_i(q_i) \quad \rightarrow \quad \max_{x,q}! \tag{3.4}$$

Subject to:

$$\sum_i q_i \geq \sum_j x_{z,j} \quad (\mu_z) \tag{3.5}$$

$$C_i \geq q_i \quad (\gamma_i) \tag{3.6}$$

$$q_i \geq 0 \tag{3.7}$$

Restriction (3.5) states that production in $i \in E$ has to be at least as high as the total exports. The second restriction (3.6) ensures that production in $i \in E$ does not exceed the available capacity C_i. The strictly quasi-concave objective function (3.4) and the convex restrictions (3.5)-(3.7) form an optimisation problem, which has a unique solution. The first-order optimality conditions are thus necessary and sufficient for deriving a unique optimum if the set of feasible solutions is non-empty. The equilibrium conditions are derived using the first order derivatives of the Lagrangian of Ω_z (KKT conditions). The Lagrangian multipliers μ_z and γ_i are shadow prices for player $z \in Z$ and in region $i \in E$, respectively. The variable μ_z represents the value of a marginal unit of exports, whereas γ_i corresponds to the value of a marginal unit of production capacity. The KKT conditions can be expressed as follows:

$$\tau_{i,j} - \left(\frac{\partial p_j}{\partial x_{z,j}} + \frac{\partial p_j}{\partial \widetilde{x}_{z,j}} \frac{\partial \widetilde{x}_{z,j}}{\partial x_{z,j}}\right) x_{z,j} - p_j \left(\sum_z x_{z,j}\right) + \mu_z \geq 0 \perp x_{z,j} \geq 0 \tag{3.8}$$

$$\frac{\partial W_i}{\partial q_i} + \gamma_i - \mu_z = \alpha_i \cdot q_i^2 + \beta_i \cdot q_i + \rho_i + \gamma_i - \mu_z \geq 0 \perp q_i \geq 0 \quad (3.9)$$

$$-\sum_j x_{z,j} + \sum_i q_i \geq 0 \perp \mu_z \geq 0 \quad (3.10)$$

$$-q_i + C_i \geq 0 \perp \gamma_i \geq 0 \quad (3.11)$$

The derivative $(\partial p_j/\partial x_{z,j} + \partial p_j/\partial \widetilde{x}_{z,j} \cdot \partial \widetilde{x}_{z,j}/\partial x_{z,j}) \cdot x_{z,j}$ in (3.8) expresses player z's ability to influence the market price in $j \in I$ by strategically choosing the amount of coal supplied, subject to his conjecture of the other producers' reaction. In the case of a Cournot-Nash oligopoly, $\partial \widetilde{x}_{z,j}/\partial x_{z,j} = 0$ holds and KKT-condition (3.8) simplifies to (3.8a) under the assumption of a linear demand function. In a competitive market, however, a change of player z's supply will be fully offset by the other producers, and therefore, $\partial \widetilde{x}_{z,j}/\partial x_{z,j} = -1$ holds. In the case of perfect competition and for fringe suppliers condition (3.8) simplifies to (3.8b).

$$\tau_{z,j} + \mu_z + b_j \cdot x_{z,j} - p_j\left(\sum_z x_{z,j}\right) \geq 0 \perp x_{z,j} \geq 0 \quad (3.8a)$$

$$\tau_{z,j} + \mu_z - p_j\left(\sum_z x_{z,j}\right) \geq 0 \perp x_{z,j} \geq 0 \quad (3.8b)$$

Equation (3.1), the first order conditions (3.8) and (3.9) as well as capacity constraints (3.10) and (3.11) for all players $z \in Z$ together constitute the optimisation problem. The unique solution for this set of inequalities yields the equilibrium for this market. This mixed complementary problem was implemented using the software GAMS[33].

3.4 Dataset

The database used in this analysis stems from several extensive research projects conducted at the Institute of Energy Economics at the University of Cologne. Steam coal market data have been acquired from a multitude of different and potentially heterogeneous sources. Although steam coal market data seem scarce at first glance, various institutions, researchers, experts, and companies have published useful information. General steam coal market data are for example, published by institutions like IEA and EIA[34]. Detailed data on supply chain costs, steam coal demand, and production of major players are available from the IEA Clean Coal Centre[35]. Further publications include

[33] See Rutherford (1994) or Ferris and Munson (1998) for detailed information on complementarity programming in GAMS.

[34] See IEA (2009) and IEA (2010c), EIA (2010a) and EIA (2010b).

[35] See Baruya (2007, 2009), Minchener (2004, 2007) and Crocker and Kowalchuk (2008).

analyses from employees working for international utilities and coal industry newsletters[36]. National statistics bureaus and ministries concerned with minerals, energy, and resources provide detailed information[37]. Furthermore, company annual reports and presentations related to the steam coal market have been evaluated and expert interviews conducted. Moreover, our database is regularly discussed and reviewed with industry experts.

3.4.1 Mining Costs and Export Capacity

Costs for mining consist of overburden removal and extraction costs, processing and washing costs, and transportation costs within the colliery. The data on mining costs are based on expert interviews and the evaluation of annual reports and literature sources as described above. Since these data stem from heterogeneous sources and are mostly based on cost ranges and mining costs of representative mines, we regard our data only as proxy for real mining costs. The lack of data on some mines might cause distortions if we would model every single mine explicitly. Therefore, we fit the available data of mine mouth cash costs and mining capacity to a quadratic marginal cost function by ordinary least squares. This method yields a supply curve that comprises the main characteristics and cost levels of each mining region. Figure 3.1 gives an example of Colombian mining costs and the approximated marginal cost function. As coal qualities vary between the mining regions, calorific values are generally adjusted to 25.1 MJ/kg using data from Ritschel (2010), BGR (2008), and IEA (2009).

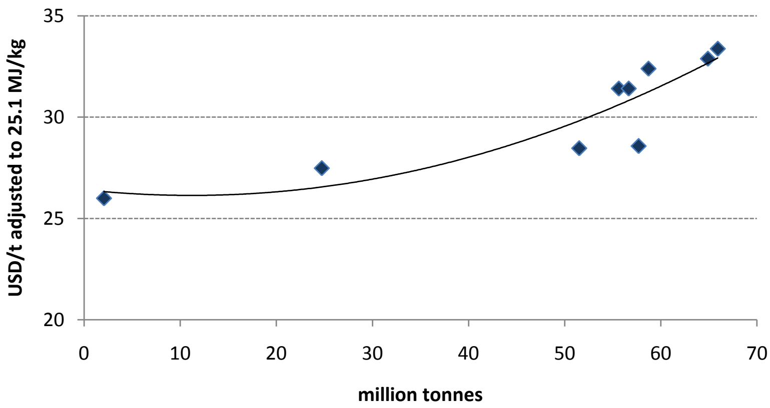

Figure 3.1: Example of FOB costs for Colombia and approximation of marginal cost function for 2006

Source: EWI coal database.

These supply curves are complemented by country and technology-specific mining cost structures and are escalated using input price data. These cost structures

[36]See e.g. Kopal (2007), Rademacher (2008), Bayer et al. (2009) and Ritschel (2007), Ritschel and Schiffer (2005). The McCloskey Coal Report is regularly reviewed.

[37]Notable examples are ABARE, US Geological Survey, Bundesanstalt für Geowissenschaften und Rohstoffe, Australian Bureau of Statistics, DANE, BLS and Statistics South Africa.

are derived from a number of sources. Detailed information for Australian open cast and underground mines is found in ABS (2006). Meister (2008), Baruya (2007), and Ritschel (2007), for instance, provide information on cost structures on a global scale. Longwalling and Room/Pillar are the predominant underground mining technologies, whereas open cast operations rely either on draglines or truck/shovel or a mix of both technologies. The cost structures indicate how much diesel fuel, steel, explosives, tyres, chemicals, electricity, and labour is used per mode of technology. The proportions of these commodities vary significantly between the four predominant extraction technologies dragline, truck/shovel, longwalling, and room/pillar (see table 3.2). Labour cost is one of the factors that typically differ among the coal-producing countries. For example, while salaries are low in countries like South Africa or Indonesia, they are considerably higher in the USA or Australia.

Table 3.2: Input factors and relative importance in coal mining 2006

in %	*Diesel fuel and lubricants*	*Explosives*	*Tyres*	*Steel mill products*	*Electricity*	*Labour*	*Industrial Chemicals*
Room/Pillar	5-8	0-2	0	23-34	10-18	28-39	9-13
Longwalling	5-10	0-2	0	25-35	10-17	28-45	4-8
Dragline	15-19	15-21	5-10	22-27	6-11	18-33	1-4
Truck/Shovel	17-26	17-23	8-11	19-26	0-3	18-35	1-4

Source: ABS (2006), Meister (2008), own database, see also Paulus and Trüby (2011).

The mining cost curves are escalated according to the cost structures using the price index data for the above-mentioned commodities from various statistical offices. Furthermore, productivity figures and country-specific exposures to fluctuations of exchange rates are included. This method yields the shifts in supply curves for the period of 2006-2008.

Generally, coal supply costs increased world-wide during 2006 and 2008 due to input price escalation. Table 3.3 presents an overview of the cost increases for the model mining regions. Clearly, mining cost escalation affected producers differently. Major exporters with a large share of open cast production, like Indonesia or Colombia, generally experienced higher cost increases. Producers with a high proportion of underground mines, like the U.S., South Africa, or Australia, were less affected. This is due to the different cost structures of underground mining operations. Underground mining technologies rely to a larger extent on labour costs, electricity prices, and locally sourced materials. With the exception of steel products, which are also an important input in deep mining, the increasing prices of fuel and oil derivatives, explosives, and tyres did hardly raise underground mining costs.

TABLE 3.3: Average FOB costs in USD/t and export capacity (adjusted to 25.1 MJ/kg)

	Average costs			Export capacity		
	2006	*2008*	*cost increase*	*2006*	*2008*	*capacity increase*
Indonesia	33	44	33%	154	197	28%
Colombia	31	42	34%	59	74	25%
China (Shanxi)	34	44	30%	62	45	-27%
USA (Central Appalachia)	46	57	23%	25	31	25%
Venezuela	32	38	19%	9	9	0%
Vietnam	29	38	32%	27	22	-18%
Spitsbergen	41	52	26%	2	4	67%
Queensland/open cast	33	41	24%	33	37	13%
Queensland/underground	33	37	14%	8	8	5%
New South Wales/open cast	34	42	23%	52	59	12%
New South Wales/underground	34	41	21%	27	31	15%
South Africa/open cast	28	36	28%	45	46	4%
South Africa/underground	32	41	25%	24	25	5%
Russia (Baltic)	48	64	34%	61	69	14%
Russia (Pacific)	40	48	19%	15	19	22%
Poland	58	79	36%	8	5	-38%
Total				*611*	*681*	12%

Source: Own calculations/EWI coal market database; export capacity data based on Kopal (2007), Rademacher (2008),Bayer et al. (2009).

Steam coal export capacity increased by about 12% between 2006 and 2008 (table 3.3). In the Pacific basin, much of the growth came from Indonesia and Australia, thus expanding their supply capacity. In the Atlantic market, Colombia increased its export capacity by about 25mt and became the largest steam coal exporter in the Atlantic market in 2008. Export capacity data were primarily derived from Kopal (2007), Rademacher (2008), and Bayer et al. (2009) and adjusted for energy content.

3.4.2 Transport Costs, Port Handling Fees, and Seaborne Freight Rates

Inland transport costs depend on the transportation mode and the distance from the coal fields to the export terminal. Coal is mainly hauled by rail and truck and, in some cases, by river barge. Inland transport costs vary between the mining regions. While they are below 4 USD/t for the bulk of the Colombian production, they may be as high as 25 USD/t for transport from the Russian Kuzbass basin to the Baltic ports. We estimated the relative impact of diesel fuel and electricity cost escalation using the relative importance of truck and railway haulage for the main transport routes. Port handling fees include costs for unloading, storage, and loading onto vessels. Country-specific average inland transport cost and port handling fees are added to the mining cost curve to derive FOB supply functions. Seaborne bulk carrier freight rates are a major cost component of internationally traded steam coal. For determining seaborne transport costs we use root-functions as freight cost functions based on distance. To determine these functions we regressed distances against a dataset of freight cost observations for

TABLE 3.4: Steam coal reference demand in million tonnes adjusted to 25.1 MJ/kg

	Europe	*Japan*	*India*	*Latin America*	*China*	*Taiwan*	*Korea*	*North America*	*South East Asia*
2006	187	110	26	9	46	60	62	42	29
2008	184	118	35	16	46	60	72	38	36

Source: IEA (2008, 2010a), Ritschel (2007, 2009a).

both model years. We use these cost functions to determine consistent freight rates for every possible shipping route in the model.

3.4.3 Demand Data

As described in Section 3.3 we assume linear steam coal demand functions for all importing regions based on reference quantities and prices as well as elasticities (see table 3.4 for reference volumes). We used the MCIS steam coal markers for reference price data in the model. A general shortcoming of the literature on market conduct in global steam coal trade is the treatment of the demand side. Usually, assumptions on elasticities are drawn from empirical analyses found in the literature and subsequently elasticity sensitivities are computed[38]. This paper presents an elasticity analysis for Europe, the largest import demand region on the maritime market. Demand elasticities for other regions are based on an extensive literature review.

Several econometric analyses on short-run steam coal demand elasticities and inter-fuel substitution have so far been published (see table 3.5 for an overview of the most important articles). Empirically estimated elasticities fall in the range of -0.05 to -0.57. Although the analyses differ with regard to coverage, time-frame, and methodological approach, all authors find that price elasticity of steam coal demand is inelastic (|Elasticity|<1).

TABLE 3.5: Overview of short-run coal demand elasticities in the literature

Article	*Methodology*	*Time period*	*Sector*	*Region*	*|Elasticity|*
Dahl and Ko (1998)	Panel data analysis	1991-1993	Electricity	U.S.	0.16-0.26
Ko (1993)	Time series analysis	1949-1991	Electricity	U.S.	0.25
Kulshreshtha and Parikh (2000)	Time series analysis	1970-1995	Electricity	India	0.34
Söderholm (2001)	Panel data analysis	1984-1994	Electricity	Europe	0.05-0.29
Masih and Masih (1996)	Time series analysis	1970-1992	all sectors	China	0.25
Ball and Loncar (1991)	Time series analysis	1978-1988	Electricity	OECD	0.16
Chan and Lee (1997)	Time series analysis	1953-1994	all sectors	China	0.26-0.32
Ko and Dahl (2001)	Panel data analysis	1993	Electricity	U.S.	0.57

Short-run steam coal demand elasticity depends on various factors, such as the power plant mix, the price of alternative fuels (particularly natural gas and, in some regions, fuel oil), the price of emission certificates, and total electricity demand, to name but a

[38]See e.g. Haftendorn and Holz (2010) who choose elasticities during the calibration process based on Dahl (1993) or Graham et al. (1999) who test for several elasticities figures. Kolstad and Abbey (1984) assume demand elasticities of -0.6 for all regions.

few. Since these factors vary over time, it is likely that some of the figures presented in table 3.5 are outdated today.

We therefore conduct a steam coal demand analysis for Europe using the dispatch module of a Dispatch and Investment Model for Electricity markets in Europe (DIME). DIME is a large-scale linear optimisation model for the European electricity market that simulates hourly dispatch taking account of conventional and renewable generation technologies[39]. We calibrate the model with actual data for the years 2006 and 2008, including the European power plant fleet, gas, fuel oil, and CO_2 emission prices as well as country-specific load data. Then, we iteratively test a high number of (equidistant) steam coal price points. The model computes the cost-minimal power plant dispatch and steam coal consumption subject to the coal price. Subsequently, we fit a linear function to the data using OLS, from which we derive the elasticity at the reference point. Steam coal demand elasticity for the European electricity sector is estimated to be -0.12 in 2006 and -0.43 in 2008. The difference between these two figures stems from the varying gas and CO_2 emission prices and thus their impact on the clean dark spread in the reference point[40]. During 2006 the clean dark spread was favourable for coal-fired power plants, whereas in 2008, with an increasing emissions price and a similar gas price as in 2006, the clean dark spread decreased. Hence, around the reference point (high coal price in 2008; low coal price in 2006) the elasticity was higher in 2008 than in 2006.

However, these results cannot be generalised for all demand regions, since they depend on a number of factors that usually differ regionally[41]. In the presented paper, we use the estimated elasticities for Europe and assume a steam coal demand elasticity of -0.3 for all other importing regions for both years. This assumption is based on the above-mentioned literature review.

3.5 Simulation Design

The focus of our analysis is on seaborne steam coal trade for which a spot market with several well-established price indices exists[42]. Hence, we model only dedicated export

[39]See Bartels (2009). For applications of this model see e.g., Paulus and Borggrefe (2010), Nagl et al. (2011) or Fürsch et al. (2012). A detailed description can be obtained from www.ewi.uni-koeln.de.

[40]The clean dark spread is the margin that a coal-fired power plant earns given a certain electricity, coal, and emissions price. European gas spot market prices were 22 EUR/MWh in 2006 and 24 EUR/MWh in 2008 (APX, 2010). CO_2 emission prices were 17 EUR/tCO_2 in 2006 and 22 EUR/tCO_2 in 2008 (EEX, 2011).

[41]For instance, regionally differing gas prices or the installed capacity, availability, and efficiency of the fleet. In some regions, the competing generating technology may not be gas-fired plants. Decreasing or increasing electricity demand also has an impact on coal-demand elasticity. Moreover, emissions trading systems are not implemented in all regions (the U.S., for example, has no GHG emissions trading system but has an NO_x trading system).

[42]See Ekawan and Duchêne (2006).

mining capacity[43].

The supply structure in the steam coal trade market is heterogeneous. It consists of large state-run mining entities, several privately-owned international mining companies, and a large number of small national players. Furthermore, production regions are widely dispersed over the globe, and so far no formal cartel such as the OPEC has been established. Therefore, in one scenario we test for a competitively organised steam coal trade market.

However, the majority of internationally traded coal is produced by only four countries with a primarily export-oriented mining industry and a favourable cost situation: Indonesia, Australia, South Africa, and Colombia. Indonesia was a member of OPEC until 2008, when its oil reserves were depleted. Very quickly it has become the world's largest steam coal exporter (Indonesian coal exports grew by 45% between 2005 and 2008). The issue of mining concessions is government controlled and is nowadays only granted to Indonesian companies[44]. Hence, currently, the majority of steam coal production and infrastructure is controlled by large Indonesian conglomerates or the government. International coal trade is an important national revenue earner, which may favour non-competitive behaviour on a government level. Australia, Colombia, and South Africa have privately owned mining industries[45], but the crucial export terminals are controlled by consortia consisting of the major players in the country[46]. Clearly, all of these countries have the *potential* to act strategically and can be interpreted as national oligopolists.

Similar to Kolstad and Abbey (1984), we assume that individual producers act as price takers, but oligopolistic rent is accrued on a country level, for example through taxes, royalties, quotas, or collusive port throughput agreements. This allows us to use aggregate national supply functions[47]. The non-competitive scenario is designed as follows: Australia, Indonesia, Colombia, and South Africa act as non-cooperative Cournot players. Additionally, China is assumed to act as a Cournot player. China is the largest steam coal producer in the world and has the potential to influence the seaborne

[43]Export capacity data are based on Kopal (2007) and Rademacher (2008) but are adjusted for energy content and in some cases downgraded if other sources suggested so.

[44]See Baruya (2009).

[45]Nevertheless between 65% and 95% of steam coal exports of South Africa, Colombia and Australia are controlled by six large multinational companies (Xstrata, AngloAmerican, BHP Billiton, Rio Tinto and Drummond). See Murray (2007) and Wacaster (2008).

[46]BHP Billiton and AngloAmerican, are major shareholders of the Newcastle Infrastructure Group, which operates the Newcastle Coal Terminal, the main export hub in New South Wales. The largest coal terminal in the world, Richards Bay (South Africa) is jointly owned by all major producers in the country amongst them: BHP Billiton, AngloAmerican and Xstrata. The main export terminal in Colombia, Puerto Drummond, and Puerto Bolivar are owned by Drummond and a consortium consisting of Xstrata, BHP-Billiton, and AngloAmerican, respectively. Moreover, these companies are vertically integrated and also own and operate the domestic coal transport infrastructure (Baruya, 2007).

[47]Our Cournot model formulation can be interpreted as a quota system that restricts exports to the Cournot-Nash outcome. Other Cournot model formulations with taxes instead of quotas of course produce equivalent outcomes (see e.g., Kolstad and Abbey (1984)).

market significantly. Chinese authorities have intervened regularly in resource markets and have continuously reduced steam coal export quotas[48]. Russia, USA, Venezuela, Vietnam, Norway and Poland act as price takers and constitute the competitive fringe. All of these countries have a mining industry that primarily serves the domestic market or is very small.

3.6 Results

3.6.1 Simulation Results for the Year 2006

Figure 3.2 depicts actual price data and simulated model prices for the perfectly competitive and the Cournot oligopoly scenario for four major importing regions[49]. Clearly, the marginal cost-based price matches the actual import price in Europe. Actual prices were, however, higher than marginal costs of delivery in Japan, Taiwan, and South Korea. From a price perspective, the hypothesis of Cournot-Nash behaviour can be rejected, since oligopolistic prices exceed actual prices significantly in 2006.

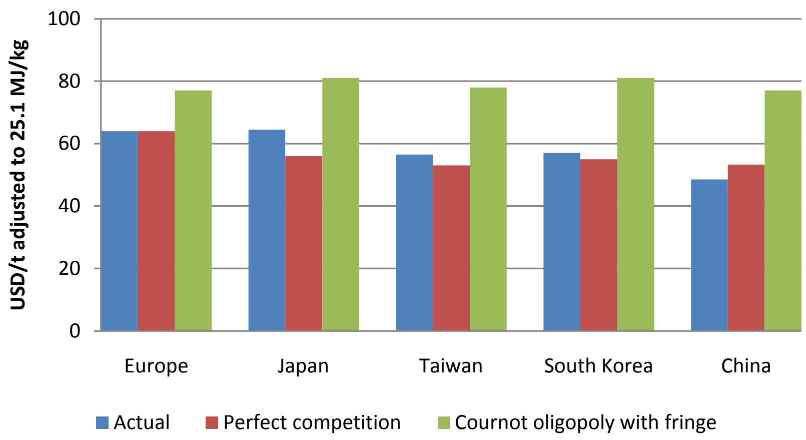

Figure 3.2: Comparison of actual and simulated prices in 2006

Source: Own calculations/MCIS-steam coal marker prices.

Table 3.6 reports actual and simulated steam coal trade volumes between exporting and importing regions for the year 2006 in million tonnes. In comparison to the price analysis, the picture is less clear-cut when the focus is on trade flows. In general, trade flows in the perfect competition setup fit the actual trade pattern better, since total

[48]Chinese coal policy shares some interesting similarities with its policy on rare earths. Chinese government has introduced an export limit on coal and on rare earths and has repeatedly cut these limits (Hurst, 2010, Sagawa and Koizumi, 2008). Moreover, it restructures and consolidates both its coal mining and its rare earths mining industries to gain more control (Hurst, 2010, Peng, 2011). In the coal sector, companies have to qualify as exporters. So far only state-run companies are eligible for export licences (Baruya, 2007).

[49]For reasons of consistency, we use the McCloskey's Asian marker, North West European marker, and Japanese marker for deliveries in the 90-day forward period. These markers are adjusted to 6,000 kcal/kg and serve as a spot price indicator.

supply is too low in the non-competitive scenario. Main trade relations in the real market match the major importer/exporter relations in the perfectly competitive scenario well in the Atlantic market[50]. This supports the hypothesis that the international steam coal trade market was, to a certain degree, subject to competitive market mechanisms in 2006. However, the actual trade pattern is more diversified than the competitive one, particularly in the Pacific Basin[51].

TABLE 3.6: Comparison of actual and simulated trade flows in million tonnes (energy adjusted)

	South Africa	*Russia*	*Venezuela*	*Vietnam*	*Indonesia*	*Colombia*	*China*	*USA*	*Australia*	*Poland*	*Norway*
Actual 2006											
Europe	56	59	2	1	17	28	3	6	3	8	2
North America		2	5		3	26			6		
Latin America	2		1		2	3			1		
China		1		22	14		1		8		
Taiwan		2			29		16		13		
Japan		9		3	23		16		60		
Korea		3		1	20		17		20		
India	3				17		5		2		
South East Asia	1	2			24		2				
Total	*62*	*78*	*8*	*27*	*149*	*58*	*60*	*6*	*113*	*8*	*2*
Perfect competition 2006											
Europe	69	58			6	31		13		8	2
North America			9			28			5		
Latin America									9		
China				27	18						
Taiwan					61						
Japan		13			13				89		
Korea					1		62				
India					26						
South East Asia					30						
Total	*69*	*71*	*9*	*27*	*154*	*59*	*62*	*13*	*103*	*8*	*2*
Cournot oligopoly with fringe 2006											
Europe	17	61	2		20	17	11	19	16	8	2
North America	6		6		7	7	4		7		
Latin America	2		1		2	1	1		2		
China	6			1	10	5	7		8		
Taiwan	8			9	12	6	8		10		
Japan	13	15		9	20	11	15		17		
Korea	8			5	13	7	10		11		
India	4			1	6	3	3		5		
South East Asia	4			3	7	3	4		5		
Total	*68*	*76*	*8*	*27*	*95*	*59*	*62*	*19*	*81*	*8*	*2*
		Actual			Perfect Competition				Cournot oligopoly with fringe		
Total seaborne trade		571			577				506		

Source: IEA (2008, 2010a), own calculations.

Although the oligopolistic trade pattern differs substantially from the actual trade flows, it features a higher degree of diversification. This diversification of exports stems

[50]In reality, South Africa, Russia, the U.S., and Colombia are the main suppliers to Europe. Small high-cost producers like Poland or Norway are located close to the European market and generally ship their product to Europe. The North American demand region procures most of its imported coals from Latin American suppliers.

[51]Several reasons may account for the deviations between the actual trade pattern and the competitive pattern. First, economies with a high import dependency like Taiwan, Japan, or Korea may apply import diversification strategies for reasons of security of supply. This may also explain the slightly higher prices in the real market, since these economies would usually pay a premium for their import diversification. Second, calorific values are indeed the most important quality parameter and are accounted for in the analysis. However, the chemical composition of coals in regard to ash and sulphur content, moisture, and volatile matter may be important efficiency determinants for power plants. Some power plants may be adjusted to a specific coal type, or certain types of coal from different regions are often blended to optimise coal quality at the import terminal. Third, long-term bilateral contracts are still quite common in international coal trade. Finally, statistical errors and differences in energy-mass conversion may cause differences in statistics of traded volumes.

from the oligopolists' profit maximisation: a Cournot player exports to a certain market until marginal revenue equals marginal costs there. With a high market share in a certain importing region, perceived marginal revenue for the exporter is low, thus making it profitable to diversify the export structure. This may justify trade with regions that would not occur cost-wise in a perfectly competitive market.

Especially, major players in the Pacific Basin like Australia, Indonesia, and China have an especially diversified supply structure in reality. Competitive behaviour would suggest that China ships all of its exports to Korea, whereas in the actual market, China trades the bulk of its exports with three Asian economies: Japan, Taiwan, and Korea. Although Indonesia's supply structure is more diversified by nature due to its high production, the cost-minimal solution would imply that Taiwan procures all of its imports from Indonesia. Although Taiwan is a major importer of Indonesian coal, it sources its imports from several exporters. In the non-competitive market structure setup, even high-cost fringe producers like the U.S. or Russia increase their market share. Since oligopolistic players withhold exports, prices rise and the fringe can capture rents by expanding its supply.

The results for 2006 reveal a relatively high degree of competition, particularly in the Atlantic market. In the Pacific market, we note that prices exceed marginal costs of delivery and that the actual trade pattern is more diversified than the competitive one. Hence, the market outcome is not fully efficient from a welfare perspective, suggesting that some non-competitive mechanisms also apply. Furthermore, we reject our non-competitive oligopoly with competitive fringe scenario. In this setup, too much quantity is withheld, and consequently, prices are high when compared to actual data.

Haftendorn and Holz (2010) also find that prices deviate from marginal costs and real market trade flows are more diversified than in the competitive scenario. Our results are qualitatively consistent with their conclusion that steam coal trade is better characterised by perfect competition than by a non-cooperative Cournot game in 2006.

3.6.2 Simulation Results for the Year 2008

Analysis of the seaborne steam coal market in 2008 reveals a different picture. In 2008, steam coal import prices soared to very high levels of more than 140 USD/t on average in the core demand regions (see figure 3.3). Clearly, by comparing competitive (marginal cost-based) prices of 2006 (see figure 3.2) with corresponding prices of 2008 (see figure 3.3), we see that marginal costs of supply increased significantly between 2006 and 2008, too. However, the cost increment is not high enough to cause price spikes as those seen in 2008. For example, import prices in Europe were 147 USD/t, while simulated marginal cost prices (including seaborne freight rates) are 100 USD/t. Consequently, the remaining spread of 47 USD/t between marginal costs and actual prices is too large to justify perfectly competitive conduct on the seaborne trade market in this year. However, we can also reject the hypothesis of the Cournot-Nash oligopoly with competitive fringe in this market from a price perspective. Oligopolistic mark-ups are too high, and prices in the Cournot setup again exceed actual prices substantially.

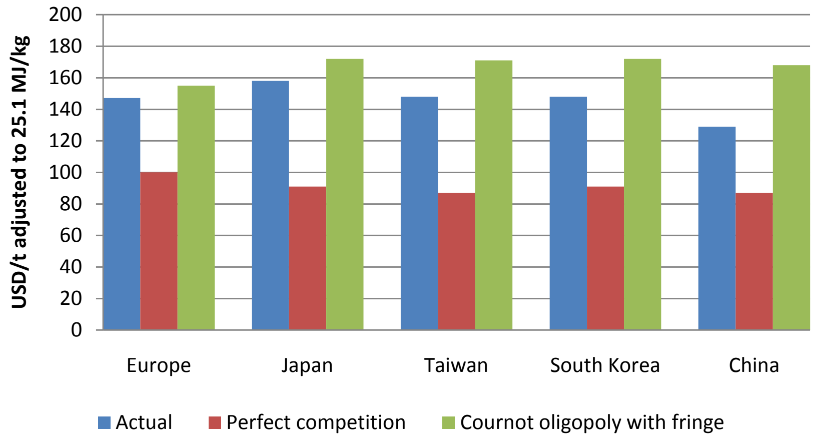

Figure 3.3: Comparison of actual and simulated prices in 2008

Source: Own calculations/MCIS-steam coal marker prices.

With regard to trade patterns, we observe that (as in 2006) certain competitive mechanisms seem to apply (see table 3.7). Trade relations in the Atlantic market are quite accurately simulated in the competitive setup. The export structures of Colombia and Russia, both major suppliers for Europe, are still well approximated by the competitive model. However, the role of South Africa clearly changed. While South African exporters shipped 90% of their production to Europe, this share has decreased to less than 70% in 2008. This shift of exports to the Pacific Basin is not efficient. The competitive scenario shows that, from a cost minimisation perspective, South African coals should be directed to the European market. Thus, in the real market, South African exporters could accrue higher rents in the Pacific Basin, indicating that prices were inefficiently high in Asian import regions.

Furthermore, U.S. exports to Europe deviate significantly with that of the U.S., supplying about 15 mt more than in reality. This result may be explained by the neglect of the U.S. domestic coal market in the model. Some of the export mining capacity attributed to the U.S. in the model normally serves the domestic market but generally has access to export infrastructure and the necessary coal quality to trade its product on the maritime market. However, exports depend not only on prices in the international market but also on domestic prices and contractual obligations. These issues can only be addressed by explicitly modelling the domestic markets.

Table 3.7: Comparison of actual and simulated trade flows in million tonnes (energy adjusted)

	South Africa	*Russia*	*Venezuela*	*Vietnam*	*Indonesia*	*Colombia*	*China*	*USA*	*Australia*	*Poland*	*Norway*
Actual 2008											
Europe	44	64	3	1	14	32	2	15	2	3	3
North America	1		2		2	31			1		
Latin America	2	1	1		1	8		1	1		
China		1		19	25				1		
Taiwan		1			29		11		19		
Japan	1	11		2	27		11		67		
Korea	1	9		1	26		16		19		
India	12				22		1		1		
South East Asia	2				26	2	1		5		
Total	*64*	*87*	*6*	*23*	*172*	*73*	*42*	*16*	*116*	*3*	*3*
Perfect competition 2008											
Europe	72	69				25		31		5	4
North America			5			37					
Latin America			4			12			2		
China				22	29						
Taiwan					67						
Japan									133		
Korea		19			17		45				
India					38						
South East Asia					41						
Total	*72*	*88*	*8*	*22*	*192*	*74*	*45*	*31*	*135*	*5*	*4*
Cournot oligopoly with fringe 2008											
Europe	20	69			31	24	3		28	5	
North America	4		5		7	6	2	5	7		
Latin America	2		3		3	2	1		3		
China	6			5	11	5	5		10		
Taiwan	7			13	13	7	6		11		
Japan	13	5			23	13	12	26	22		
Korea	9	13			15	8	9		14		
India	5				8	4	3		7		4
South East Asia	5			4	9	4	4		8		
Total	*72*	*88*	*9*	*22*	*119*	*74*	*45*	*31*	*109*	*5*	*4*
		Actual			Perfect Competition				Cournot oligopoly with fringe		
Total seaborne trade		606			677				577		

Source: IEA (2010a), own calculations.

Simulated trade flows are again more distorted in the Pacific market. In reality, the three major players in the Asian market, Australia, Indonesia, and China, decide on a trade pattern that deviates significantly from the welfare efficient solution. Although the trade pattern of 2006 already suggested this, the effects are more pronounced in 2008. In light of competitive prices that are considerably lower than actual prices, the hypothesis of perfect competition on the seaborne market is arguable in 2008.

Moreover, in 2008, the efficient equilibrium quantity of 677 mt was not supplied. Instead, the total trade volume stood at 606 mt, implying that not all available supply capacity was in operation. There are, in fact, a number of possible reasons that export capacity may have been scarce during 2008[52]. Although such short-run bottlenecks are hard to quantify it seems unlikely that they add up to more than 70 mt. However, steam coal allocation also does not appear to be non-competitive in terms of the selected non-competitive setup of Cournot behaviour. As in 2006, the diversified supply structure

[52]The national market in the USA may have had an impact on exports due to contractual obligations or high demand. U.S. exports remained under their nominal capacity potential. Secondly, some export collieries may not have reached full production capacity due to strikes and bad weather conditions (see Ritschel (2009a) and Xstrata (2008)). Thirdly, interactions between the thermal coal market and the coking coal market may have had an impact. As a small proportion of a specific steam coal quality may also be upgraded to low quality metallurgical coal by washing, the boom on global steel markets in 2008 may have forced some steel mills to use coals that otherwise would have served as thermal coal.

in the Cournot setup has some appeal, but total traded volumes are again too low and simulated prices too high.

3.6.3 Sensitivity Analysis

Different assumptions for demand elasticities can have a large impact on simulated prices and traded volumes if the reference equilibrium deviates from the simulated equilibrium. We will illustrate this effect in figure 3.4. Let S be the linear marginal cost curve, D and D' the linear demand curve for different elasticity values, and E^{ref} the reference equilibrium. The reference equilibrium is determined by the reference quantity q^{ref} and the reference price p^{ref}. The capacity limit is denoted as q^{max}. The graph on the left depicts a situation in which the reference equilibrium coincides with a simulated competitive equilibrium. In this case, different elasticity values have little or no effect on prices and trade volume, as just the slope of the demand function changes, but not the intersection of demand with the supply curve.

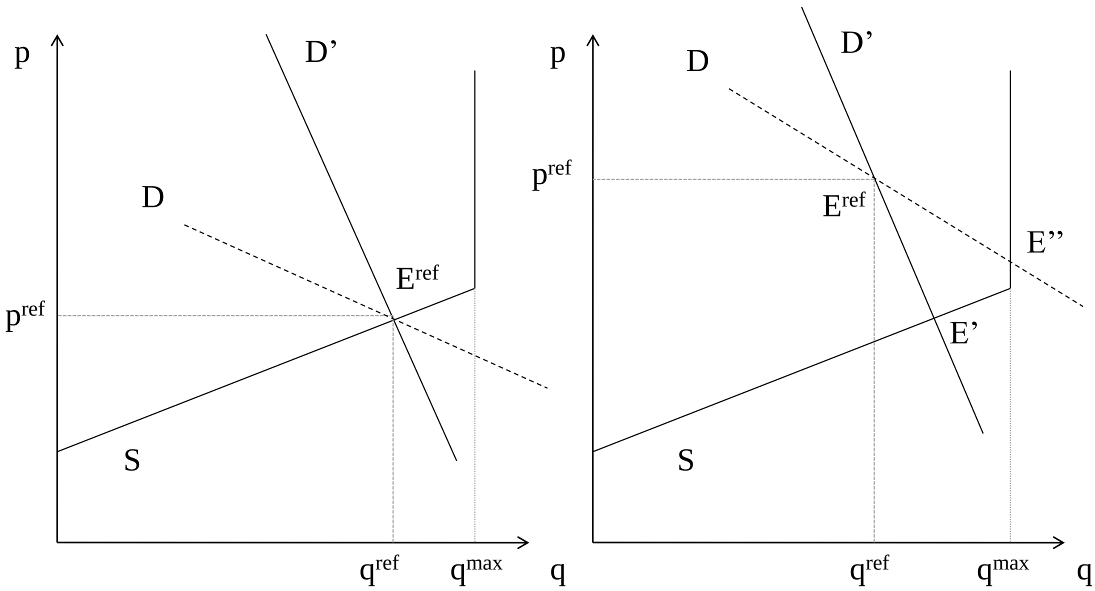

FIGURE 3.4: Comparison of competitive market equilibria under different elasticity assumptions

The graph on the right outlines a situation in which the real market equilibrium and the simulated competitive equilibrium in 2008 do not coincide. In contrast to the first setup, the reference equilibrium is not on the marginal cost curve, and different price elasticity values have a large effect and imply different model-based equilibria *E'* and *E"*. In such a situation, a competitive model cannot reproduce the reference equilibrium. Hence, either the capacity limit q^{max} was temporarily shifted to the left due to short-term bottlenecks or prices were strategically raised over marginal costs.

Consequently, we test our results presented in sections 3.6.1 and 3.6.2 for robustness by performing a sensitivity analysis regarding price elasticities of demand of importing regions. We test for the following values, which broadly fall in the range presented in table 3.5: −0.1, −0.3, −0.5 and −0.6. Elasticities are assumed not to differ between the importing regions in each simulation run. Figure 3.5 presents a model and real market prices for different elasticity runs for the year 2006.

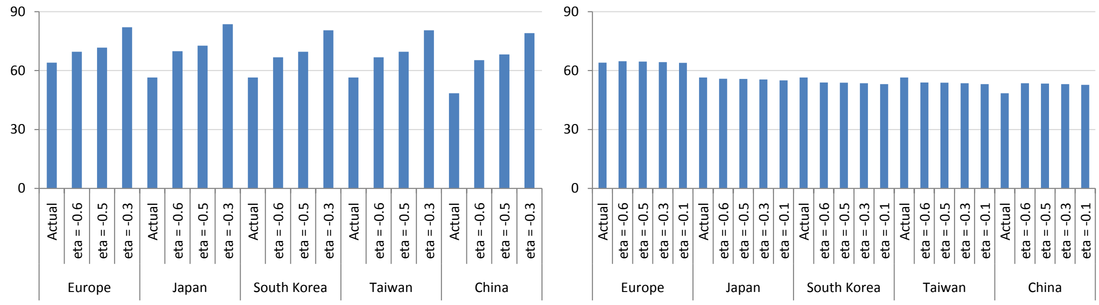

FIGURE 3.5: Prices in USD/t for different elasticity values (eta) in the year 2006 for oligopoly with fringe (left) and perfect competition (right)
Source: own calculations.

Clearly, model prices are more robust with regard to different elasticity assumptions in the competitive scenario, indicating that reference and simulated equilibrium are close to each other. Prices in the non-competitive scenario are significantly above actual 2006 price levels for all tested elasticity values. Also, capacity utilisation remains stable at 95% to 96% (see table 3.8) for different elasticities. These are indicators for competitive mechanisms to have applied in the real market during this year.

Figure 3.6 presents corresponding simulation results for the year 2008. In this case, the picture is less straightforward. In the competitive scenario, prices differ widely with regard to different elasticity values, thus indicating that reference and simulated equilibrium differ significantly. Also, simulated prices remain lower than actual prices for any elasticity tested. Although the supply capacity limit is reached in the competitive scenario for higher elasticities (−0.5 and −0.6), model prices are still below actual prices[53]. The simulated competitive market size is larger than the historic market volume (reference quantities).

[53] Actually, traded quantity (reference quantity) is lower than the competitive market volume in the simulation runs. Hence, demand would have to be infinitely price elastic (horizontal demand curve) to match competitive model prices with real market prices at the capacity limit (vertical part of the supply curve).

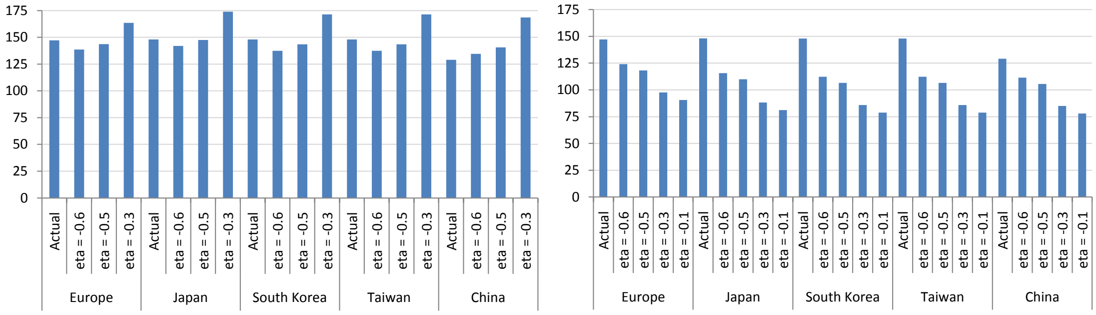

FIGURE 3.6: Prices in USD/t for different elasticity values (eta) in the year 2008 for oligopoly with fringe (left) and perfect competition (right)

Source: own calculations. Note: Results for eta = -0.1 were omitted in the left graph for the sake of clarity. In this case, prices are well above 280 USD/t in most demand regions.

Both the oligopolistic and the competitive scenarios show relatively robust prices for higher elasticities (−0.5 and −0.6). However, oligopolistic prices fit actual prices better. In the case of an elasticity value of −0.5, model prices are close to real market prices in major importing regions (except for China), and total model market volume is close to the real market outcome. However, trade flows are again distorted under the oligopoly market structure and therefore we still reject the oligopolistic scenario as an explanation for real market outcomes. See appendix B for a comparison of simulated trade flows with actual trade flows in this case.

TABLE 3.8: Capacity utilisation for different values of elasticity, in %

	Oligopoly with fringe		Perfect competition	
Capacity utilisation	2006	2008	2006	2008
eta = -0.6	85,9%	91,6%	96,0%	100,0%
eta = -0.5	85,3%	89,5%	95,9%	100,0%
eta = -0.3	83,9%	84,9%	95,5%	99,6%
eta = -0.1	82,2%	79,6%	95,0%	93,2%

Source: own calculations.

Furthermore, coal demand elasticity of more than −0.3 might seem to be unrealistic for major Asian importing countries. South Korean and Japanese coal-fired power plants experienced a major cost advantage compared to natural gas-fired power plants during most of 2008, which was also significantly higher than the cost advantage of coal in Europe (figure 3.7). As outlined in section 3.4.3, a detailed bottom-up analysis yielded a coal demand elasticity of −0.43 for the European power system in 2008. Due to the even higher advantage of coal in power generation in Asian import regions, it is therefore rather unlikely that coal demand elasticity for Asian importers has been as high as in Europe. Even after taking into account ramping capabilities and long-term fuel contracts, such high-cost advantages would probably lead to lower elasticity figures of around −0.3, the value we initially assumed in our base scenario for 2008. The cost advantage of coal in Asia in power generation stemmed mostly from the very high oil-indexed LNG prices in 2008. LNG imports in these countries comprise virtually the total gas supply in Asian countries.

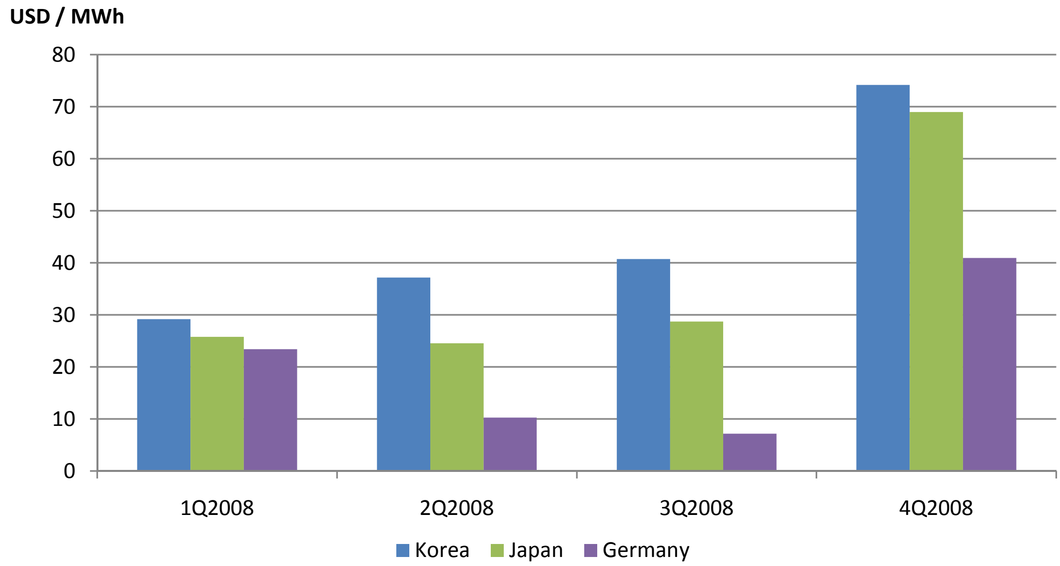

Figure 3.7: Cost advantage of coal vs. natural gas in power generation

Source: IEA (2010a,b), EEX (2011). Note: We assume average coal power plant efficiencies of 41% (Japan), 40% (Germany), and 36% (Korea) (IEA, 2010b). Assumptions for average gas power plant efficiencies are 47% (Germany, Korea, Japan). Carbon intensities are 0,335 tCO_2/MWh_{th} for coal and 0,201 tCO_2/MWh_{th} for natural gas (Nagl et al., 2011).

3.7 Discussion of 2008 Results

In general, the elasticity analysis confirms that competitive models are unable to reproduce real market outcomes in terms of prices and traded quantities in the year 2008. This result is, however, dependent on the availability of supply capacity. The supply capacity analyses conducted by Kopal (2007), Rademacher (2008), Bayer et al. (2009), as well as Rademacher and Braun (2011) demonstrate that substantial capacity expansion projects came on line in 2007 and 2008. According to our analysis, total (name-plate) supply capacity would have been sufficient to meet demand in 2008 without rationing for elasticities below -0.3. For higher elasticities, demand is rationed to some degree, but actual prices still exceed model prices.

The elasticity analysis also confirms that a Cournot market structure for trade market players is also not able to explain the market outcome in 2008 satisfactorily. However, some objections regarding competition in steam coal trade remain: first, port ownership structure in major exporting countries like Colombia or South Africa, where consortia of multinational mining companies commonly operate the crucial export terminals, may give them the *potential* to withhold quantities by adjusting coal through-put. Second, Indonesia and China have recently developed national coal strategies that give their national authorities tighter control over production and exports and thus the *potential* to restrict exports. Both countries have intervened in resource markets before – Indonesia as a former member of OPEC and China as the dominant supplier of rare earth elements.

Other non-competitive strategies which differ from simple simultaneous-move Cournot games might also help in explaining trade in 2008. In our opinion, another quite suitable non-competitive concept is that of pivotal suppliers. In a tight market, one or several individual suppliers may be pivotal in a sense that, without (part of) their supply, capacity demand would have to be rationed. A prominent historical example of such pivotal suppliers can be seen in the case of the Californian Electricity market during summer 2000 (see e.g., Joskow and Kahn, 2002). In the steam coal trade market, short-term bottlenecks may have additionally tightened supply in 2008 so that even individual large companies may have been pivotal in this year[54]. Even though a supplier may be pivotal occasionally, it is unclear if the exertion of market power is also profitable. Profitability depends on the distribution of his assets along the global supply curve (the slope of the individual marginal cost curve) as well as on the gradient of the demand curve and thus the price increment a withheld unit yields. Such a strategy may explain why international steam coal trade appears competitive in one year and non-competitive in another year.

3.8 Conclusions

In the presented paper, we analysed the allocation and pricing of steam coal in the seaborne trade market in a model-based approach. We tested for a competitive and an oligopolistic market structure in the years 2006 and 2008. Our principal findings are three. First, despite some distortions in the Pacific market, trade flows and prices in the competitive scenario fit the actual market data well in 2006. This result is qualitatively consistent with Haftendorn and Holz (2010) and is robust for different elasticity values. Second, the competitive scenario is not able to reproduce real market outcomes in 2008. Generally, prices are too low, market volume is too high, and trade flows show an unrealistically low degree of diversification in this scenario. Third, the assumed oligopoly scenario cannot explain market equilibria in any year either, but the trade pattern is generally more realistically diversified in this scenario. Yet, model prices and total market volume fits real market data well only under certain, quite unrealistic, demand elasticity assumptions in the oligopolistic scenario.

The analysis illustrates that not all available supply capacity was utilised to satisfy import demand in 2008. Name-plate supply capacity would have been sufficient for most

[54]Other than electricity, steam coal generally is a storable commodity; however, there exist no large-scale strategic stocks like those in oil and gas markets.

elasticity values to serve demand without rationing. However, it remains unclear whether capacities were withheld strategically or if unknown bottlenecks restricted exports during this year. Although bad weather conditions and social tensions may have hampered coal exports locally, there is so far no evidence regarding the impact of such bottlenecks on the whole steam coal market. However, in light of the sustained high prices for internationally traded steam coal, it is arguable whether such bottlenecks have persisted over several years.

In the context of the pivotal role of individual suppliers in times of high demand, the importance of coal in energy supply and the inability of competitive models to reproduce recent market equilibria, further research on steam coal market economics may be interesting. We suggest that future research focus on including domestic markets as well as other non-competitive pricing strategies, such as pivotal supplier behaviour.

Chapter 4

Nations as Strategic Players in Global Commodity Markets: Evidence from World Coal Trade

4.1 Introduction

Recently, the development of global commodity prices has given serious cause for concerns about the competitiveness of global commodity markets. This is especially true for natural resource markets and the trade of fossil energy fuels in particular. While the existence of a coordinated strategic trade policy on the world crude oil market has been evident since the foundation of OPEC in the 1960s, other markets for natural resources have been politicised only recently. A prominent example is the rare earth elements industry in China. Since around 2008, the Chinese government made significant efforts to bring this resource sector under tight control by industry consolidation, creation of strategic stocks, and, most importantly, by imposing trade restrictions upon exports of rare earth elements. Whether the aim of this policy was indeed the conservation of domestic resources, the preparation of monopoly power exploitation, or an 'economic weapon' against high technology nations like Japan and the West has been recently discussed (Stone, 2009). Both examples also indicate the variety of trade policy instruments. Next to cartelisation and export quotas, governments levy taxes on imports or subsidise exports. In markets where production takes place by a large number of small units, e.g. for agricultural products, marketing of exports is often conducted by trade associations. In other markets, exporting firms might be partly or entirely nationalised, being subject to governmental strategic influence (for instance natural gas exporters). Such trade policy instruments are intended to increase national welfare by influencing the market outcome in a non-competitive manner.

Another commodity market that has raised doubts about its competitiveness is the market for internationally traded steam coal (Trüby and Paulus, 2012). For decades, international coal trade was considered competitive since production is geographically dispersed and is carried out by a mixture of multinational private mining companies, large state-run entities, and various smaller national players. Yet recent developments in the international steam coal trade have led to concerns about market structure and conduct. And indeed, several institutional developments support the hypothesis of steam coal market distortion. Firstly, strong economic growth in Asia has led to increased coal demand and has thus shifted the centre of gravity and price setting from the Atlantic to the Pacific market area. Secondly, coal prices soared between 2006 and 2008 and have remained relatively high since then. Thirdly, several recent adjustments of national resource strategies of the People's Republic of China and Indonesia indicate an increasing potential for strategic behaviour on a national level in recent years[55].

During the period of the 11th Five Year Plan (2005-2010), the People's Republic of China has adopted several national policies in an attempt to restructure and streamline its domestic coal industry (NDRC, 2007). Further, Chinese authorities have significantly lowered coal export quotas from 100 Mt in 2003 to 47.7 Mt in 2008 and introduced export taxes for coal during this period, thus increasing their tight control over exports (NDRC, 2008).

Moreover, Indonesian steam coal production and exports have undergone a rapid expansion in recent years which was paralleled by political efforts to nationalise the mining industry. Indonesian steam coal exports jumped from 75 Mt in 2003 to an impressive 200 Mt in 2009 (IEA, 2010a). This development indicates a switch in the Indonesian national resource policy away from oil exports to coal exports. Indonesia pulled out of OPEC in early 2009 due to diminishing oil stocks and production as well as strong domestic oil demand. Therefore, Indonesia may be currently pursuing the strategy of becoming the dominant player in Asian coal markets to offset its declining oil revenues. The implementation of national resource policies in China and Indonesia has led to a structural shift of steam coal supply in the Pacific basin in recent years. It may have given the authorities of either country the potential to exert market power on a national level.

The presented paper therefore analyses the export patterns of major national players in the world steam coal market to identify if Indonesian and Chinese resource policies support the hypothesis of strategic market behaviour on a national level. It is related to the empirical literature on strategic trade policy which has been developed since the seminal papers of Brander and Spencer (1985), and Eaton and Grossman (1986), and

[55]These developments have severely affected several OECD countries and have increased concerns about security of supply, as the major coal consuming nations depend heavily on imports of steam coal. Japan, South Korea, and Taiwan import virtually all of their coals and Europe's average import dependency amounts to more than 60%.

others. Empirical literature on strategic trade in energy resource markets has so far been scarce. Many recent empirical contributions to this topic focus on international markets for agricultural goods and make use of diverse methods of analysis (see Reimer and Stiegert (2006) for an overview). Alston and Gray (2000) have developed a simulation model to investigate wheat market conduct of the Canadian state trading enterprise. Dong et al. (2006) have found evidence that a quantity setting oligopoly prevails in the international malting barley market using a menu approach. Using a calibration approach, McCorriston and MacLaren (2010) assessed the distorting impact of Chinese state trading enterprises on international agricultural markets.

We develop a static partial equilibrium model to test our hypothesis of non-competitive market behaviour exercised through strategic trade policy in the global steam coal trade. The model allows us to simulate perfect competition as well as non-competitive market structures where players act under a Cournot behaviour assumption. We design the model as a Mixed Complementarity Programme (MCP) by deriving the first order optimality conditions of the associated optimisation problem. Modelling spatial equilibria in commodity markets has already been scrutinised since Samuelson (1952) who applied linear optimisation techniques to competitive spatial markets. Takayama and Judge (1964) generalised spatial market economics for the non-linear case and multi-commodity markets and Harker (1986a) and Yang et al. (2002) developed conditions for various non-competitive spatial market equilibria. The application of such equilibrium modelling techniques to analyse market conduct is an active field of commodities research, e.g. in gas markets (Egging et al., 2010, Holz et al., 2008), in electricity markets (Lise and Hobbs, 2008, Müsgens, 2006), or in coking coal markets (Graham et al., 1999, Trüby, 2013).

The literature on non-competitive market conduct of national players in international steam coal trade so far focuses on the maritime trade market, which is a submarket of the global market and excludes domestic markets. Kolstad and Abbey (1984) were the first who applied a partial equilibrium model to analyse strategic behaviour in seaborne steam coal trade in the early 1980s. The authors find that a non-competitive market structure consisting of a duopoly and a monopsony simulated the actual trade patterns well. However, since then the steam coal trade market has changed substantially. In a recent paper Haftendorn and Holz (2010) analysed a number of major maritime coal trade routes and applied a mixed complementarity model to test if trade volumes on these routes fit competitive or oligopolistic behaviour in the years 2005 and 2006. Their results suggest that the steam coal trade market is better represented by perfect competition in the analysed periods. However, Trüby and Paulus (2012) modelled total trade market volume in an equilibrium approach and show that competitive models were unable to reproduce steam coal trade market equilibria in 2008.

Using our model, we test if national export strategies are consistent with Cournot behaviour and validate model results for 2008. We validate our results by applying a series of non-parametric tests such as the Wilcoxon-Sign-Rank test and Spearman's rank correlation coefficient test, as well as the Theil inequality coefficient. Our main finding is that perfect competition cannot explain market results, but a market structure setup with China and Indonesia acting as non-cooperative Cournot players fits observed trade flows and prices in 2008 best. Official Chinese steam coal export quotas in 2008 were consistent with simulated Chinese export volumes under a Cournot strategy.

The presented paper extends the existing literature in two important ways: first, we account for interdependencies and feedbacks between domestic and international steam coal markets by explicitly modelling all relevant coal fields. Hence, we avoid strong assumptions on export potentials and extramarginal supply costs on the seaborne trade market. Second, we outline a rationale and provide empirical evidence for strategic trade policy on a national level to profitably influence steam coal market equilibria in 2008.

The remainder of the presented paper is structured as follows: in section 4.2 we outline what implications a trade market-only vs. a global market analysis yields and then focus on potentials for market power sources of several actors. We describe the model and data used in section 4.3. Main findings are presented in section 4.4. Section 4.5 concludes the paper.

4.2 Steam Coal Market Economics

The majority of steam coals are not traded internationally but are produced and consumed in domestic markets. In 2008, total global hard coal production was 5850 Mt (Ritschel, 2009a). The two largest domestic markets are China and the USA, together comprising more than 65% of total production. About 13% of the global steam coal production is exported and traded internationally and more than 90% of international steam coal trade is seaborne.

The seaborne export market can be divided into a Pacific and an Atlantic market region[56]. Major importing regions in the Atlantic market are the USA and Europe (including neighbouring Mediterranean countries) with the United Kingdom and Germany at the top. Traditionally these importing regions are primarily supplied by South Africa, Colombia, and Russia.

The Pacific market has grown more dynamically in recent years. High quantities are imported by Japan, South Korea, and Taiwan – all three of them have virtually no indigenous coal production and therefore heavily rely on imports. However, most of the

[56]From a market integration perspective the steam trade coal market can be considered well integrated (Li, 2008, Warell, 2006). Nevertheless, we use this labelling in a qualitative sense to better structure our analysis of market actors.

growth has come from emerging import regions like India, South East Asia, and China. The supply side is dominated by Australia and Indonesia although the sustained high prices in Asia have attracted increasing spot volumes from South Africa and recently also from Colombia.

In the export market two different types of suppliers interact with each other: countries that have a dedicated export-oriented mining industry and countries with chiefly inland-oriented mining industries (Bayer et al., 2009, Kopal, 2007).The export-oriented countries primarily comprised of South Africa, Colombia, Australia, and Indonesia, and hold most of the supply capacity. These export industries usually have a cost advantage over domestic industries due to good coal qualities, low mining costs, and economical access to transport infrastructure. Countries with mainly inland oriented mining supply are China, USA, India, and Russia. These countries have some dedicated export collieries but a significant part of the mining capacity can serve both the national and the international market. However, interaction of dedicated export mines and domestic mines with export markets is usually limited: coal exporters often face a geographical disadvantage in supplying domestic markets as they are often located close to the coast within the vicinity of export terminals. Frequently these export mines are also not well integrated into the domestic transportation railway system to allow for cost efficient movement of coals to domestic power plants. Vice versa, mines serving the domestic markets are often located deeper inland[57] and face high transport costs for moving coal to the export market. Furthermore, coal quality requirements differ significantly between the export and domestic markets, which means that coal upgrading, washing, and drying could be necessary to bring domestic coals to export standards.

4.2.1 Market Structure

Before we formally investigate non-competitive behaviour in the steam coal market we informally discuss if there are indications that participants do indeed have the potential to exercise market power. Market power may be exerted by large coal producing and exporting countries in the steam coal market. This holds especially true for China and Indonesia.

China has increasingly made use of policy instruments, i.e. quotas and/or taxation, to control participation of Chinese firms in the international trade market in recent years[58]. Firstly, political regulations require domestic mining companies to apply for special licenses which allow for a predefined export volume. Quotas on steam coal are set and allocated by Chinese institutions annually; nevertheless they may be subject to readjustments in case of political or economical requirements. The total export volume

[57] E.g. the Powder River Basin in the U.S., the coal bearing regions of Shaanxi and Inner Mongolia in China, or several Russian coal production regions (Schiffer and Ritschel, 2007).

[58] Similar government policies on various raw materials are documented by Hurst (2010).

restriction for steam coal in 2007 was 70 Mt and was reduced to 47.7 Mt in 2008 (NDRC, 2007, 2008). Secondly, the Chinese government levies export taxes on steam coal. In 2008 export taxes for steam coal were increased to 10% from 0% in 2007 (TRCSC, 2008). These taxes significantly increased costs of Chinese coal on the trade market and thus may have had an additional impact on actual export volumes. Finally, political requirements in the coal industry consolidation process have added heavy restrictions on market entry which have strengthened the position of a few very large state-controlled coal companies (Sun and Xu, 2009).

While indications for market power executed on a nation-wide level are less obvious in Indonesia, there exists a mine ownership structure which is quite special: mining rights were awarded mostly to international mining companies in the early eighties. However, foreign investors were obliged to offer at least fifty one percent of shares to Indonesian companies or the government after ten years of mine production (Baruya, 2009). Mining rights awarded in the nineties and later went exclusively to Indonesian companies. This led to the current situation, where the majority of steam coal mine production facilities in Indonesia are owned by large Indonesian consortia[59] or the government. The government is also actively controlling export volumes to decrease speed of reserve exploitation as well as to cover rapidly growing domestic demand (Kuo, 2008). An additional aspect is Indonesia's geography: a large amount of steam coal can be shipped by barges via the navigable rivers of Kalimantan to offshore loading terminals or directly to Thailand or South China (Schiffer and Ritschel, 2007). This means that Indonesian export infrastructure is virtually not capacity constrained, which could have allowed Indonesia to export higher volumes than it actually did in 2008. One possible explanation could be that Indonesia actively pushed to limit exports in order to keep international market prices at a higher level.

The exertion of market power may be supported by important barriers to entry and capacity expansion restrictions in the steam coal market. Firstly, high political risk and/or the lack of financial resources and technical capability are effective barriers against the market entry of developing countries with thus far untapped high quality coal fields like Botswana, Zimbabwe, and Madagascar. Secondly, export capacity expansion usually requires coordination of infrastructure and mining capacity upgrading, with different stakeholders involved. This process can be very slow, as the example of South Africa shows, where mining companies upgraded production and export terminal facilities but national railway expansion still lags behind. Such restrictions are particularly delaying for greenfield projects which need access to transport infrastructure.

[59]One example is PT BUMI Resources which owns the mining companies PT Arutmin and PT Kaltim Prima Coal which together accounted for 54 Mt in 2007 or 32% of Indonesia's total steam coal exports.

4.2.2 Implications of an Export Market Analysis vs. an Integrated Analysis of Export and Domestic Markets

In the case of the coal market, previous literature has so far focused on testing for non-competitive behaviour in the export market. Even though interaction between domestic supply and dedicated export supply is sometimes hampered by transport costs, limited transport capacity, or coal quality, we argue that interaction between domestic markets and international trade does exist [60].

Proposition 4.1. *If the export market price is sufficiently high, and dedicated export capacities are constrained, then dedicated domestic production will enter the global market even if it has a cost disadvantage.*

Proof: see appendix C.

Intuitively, domestic supply will enter the export market if marginal costs (including the cost disadvantage) equal export prices and if the market is competitive. In this case a setup only taking into account the trade market will be rendered inconsistent. If the market is not competitive, the same holds true. However, export market prices have to be higher; in this case marginal export revenues (including a mark-up) have to equal marginal costs. Coal prices in the export market, and thus marginal revenues, were particularly high in 2008 (IEA, 2010a) which makes an interaction of domestic supply and export markets quite likely.

Based on the information about the current market structure we define three hypotheses for our investigation of potential non-competitive behaviour in the steam coal trade market:

H1: Steam coal market results in 2008 correspond to a perfectly competitive market setting.

H2: Indonesia acts as a strategic national player in the steam coal export market facing a competitive fringe of other producers.

H3: China and Indonesia both act as non-cooperative strategic national players in the steam export coal market facing a competitive fringe.

In the following, we will develop a large-scale empirical model to verify which hypotheses we can reject.

[60]This is especially true for some of the large domestic markets like China and the U.S. Historically, both countries have adjusted their export volume depending on the difference between the export market price and domestic market prices. Furthermore, transport infrastructure for domestic mines did not seem to be a bottleneck in 2008: chinese coal exports peaked in 2005 with exports of approximately 80 Mt. U.S. coal exports were around 100 Mt per year in the early 1990s. Therefore, coal exports in 2008 of 54 Mt in the case of China and 74 Mt in the case of the U.S. were most probably not constrained by transport capacity.

4.3 The Model

The model presented in this section is structured to find the spatial equilibrium of prices and trade flows between a given set of players and assumptions about their objective functions. We model three types of players: national producers that maximise their producer rents from sales to the export market in a Cournot fashion and at the same time maximising overall welfare in their domestic coal markets (strategic players); producers which act in a competitive manner as price takers on the export market and also as welfare maximisers in their domestic coal markets (competitive fringe); and demand regions without significant coal production which act as price-takers. All producers maximise profits subject to a number of capacity constraints and energy balance equations[61].

As demonstrated by Kolstad and Burris (1986), Salant (1982), and recently by Lise and Krusemann (2008) and by Montero and Guzman (2010), different types of Cournot games can be mapped by a term which is a producer's conjecture about the response of other producers to a change in its output. This term can be inserted in the producer's pricing equation to reflect that player's degree of market power. This term can be viewed as oligopolistic rent of the producer trading at a price above his marginal costs of supply.

TABLE 4.1: Model sets and indices

$n \in N$	Model region nodes
$m \in M \subset N$	Mining region nodes
$e \in E \subset N$	Export terminal nodes
$d \in D \subset N$	Demand region nodes
$(i, j) \in A \subset N \times N$	Transport arcs
$p \in P$	Model players
$m \in M_p \subset M$	Mine regions controlled by player p
$e \in E_p \subset E$	Export terminals controlled by player p

[61]We model energy flows which accounts for consumers buying energy, not mass. All capacities and cost functions for production and transport are normalised to a standard coal energy content in each mining region. This methodology has already been used by Paulus and Trüby (2011) and Trüby and Paulus (2012). For the sake of simplicity we suppress the energy-mass parameters in the model formulation.

Table 4.2: Model parameters

C_m^p	Production cost function of player p in mine region m
Cap_m^M	Mining capacity in mining region m
Cap_e^E	Throughput capacity at export terminal e
$Cap_{(n,n')}^T$	Transport capacity between node n and node n'
$c_{(n,n')}^T$	Transport costs between node n and node n'
c_e^E	Turnover costs at export terminal e
a_d	Intercept of inverse demand function in demand region d
b_d	Slope of inverse demand function in demand region d
$t^{p\to d}$	VAT adjustments for exports from player p to demand region d
$r^{p\to d}$	Player p's aggregate conjecture for demand region d of how exports of all other competitors change given a change in its own export volume

Table 4.3: Model variables

s_m^p	Production of player p in mining region m
$q_{(n,n')}^p$	Transport volume of player p from node n to node n'
v_d	Import price for player p in region d
x_d^p	Trade-flow from player p from mining region m to demand region d
λ_n^p	Dual variable associated with the energy balance constraint representing marginal costs of supply of player p to node n
μ_m^p	Dual variable associated with the mine capacity constraint representing mine capacity scarcity rent of player p in mining region m
ϵ_e^p	Dual variable associated with the export terminal capacity constraint representing export capacity scarcity rent of player p in export terminal e
$\phi_{(n,n')}$	Dual variable associated with the transport capacity constraint representing transport capacity scarcity rent on arc $a_{n,n'}$

4.3.1 Model Statement

The model contains a topology of nodes $n \in N$. All nodes can be subdivided into mining regions $m \in M$, export terminals $e \in E$, and demand regions $d \in D$ so that $N = M \cup D \cup E$. The roles of nodes are mutually exclusive $M \cap D = \emptyset$, $M \cap E = \emptyset$ and $D \cap E = \emptyset$. Furthermore there exists a set of players $p \in P$. In our model, players are nations with significant steam coal production. Players $p \in P$ control mining regions $m \in M_p$, export terminals $e \in E_p$, as well as demand regions $d \in D_p$. Mining regions can only be controlled by one player $M_p \cap M_{p'} = \emptyset,\ \forall\, p \neq p',\ \ p, p' \in P$. This relation also holds true for export terminals $E_p \cap E_{p'} = \emptyset,\ \forall\, p \neq p',\ \ p, p' \in P$. Nodes are connected by transport arcs $(i, j) \in A \subset N \times N$. Sets, parameters, and variables of the model are listed in table 4.1, table 4.2, and table 4.3 respectively.

The remainder of this section is organised as follows: we first develop the optimisation problem, then we state the corresponding first-order optimality conditions solved by each player type. The first-order conditions together with the market-clearing conditions define the Nash-Cournot game for the worldwide steam coal market.

The variables in parentheses on the right hand side of each constraint are the Lagrange multipliers used when developing the first-order conditions. The complementary slackness condition is indicated by a $\perp$ sign, where $0 = x \perp y = 0 \Leftrightarrow x^t y = 0$ for vectors x and y.

Profit Maximisation of Producers

Player $p \in P$ maximises his pay-off which is defined as producer rent from the export market plus overall welfare from domestic coal markets minus costs of production, shipping, and turnover. The pay-off function $PO_p\left(z_p\right) : \mathbb{R}^{|M_p|+|A|+|D|} \mapsto \mathbb{R}$ and the corresponding decision vector z_p can then be written as:

$$\begin{aligned} \max_{z_p \in \Omega_p} PO_p\left(z_p\right) = & \sum_{d \in D_p^-} v_d\left(X_d^- + x_d^p\right) x_d^p + \sum_{d \in D_p} \int_0^{X_d} v_d(u) \mathrm{d}u \\ & - \sum_{m \in M_p} C_m^p(s_m^p) - \sum_{(n,n') \in A} q_{(n,n')}^p c_{(n,n')}^T - \sum_{(e,n') \in A} q_{(e,n')}^p c_e^E, \end{aligned} \tag{4.1}$$

with $X_d^- = \sum_{p' \in P^-} x_d^{p'}$. PO_p being continuously differentiable and concave in the case that C_m^p and v_d are continuously differentiable and C_m^p is convex and v_d is concave. Profit maximisation for every producer $p \in P$ is constrained by a set of restrictions for transport and production capacities (dual variables in parentheses):

$$Cap_m^M - s_m^p \geq 0, \qquad (\mu_m^p) \qquad \forall p \in P,\ m \in M_p, \tag{4.2}$$

$$Cap_e^E - \sum_{(e,n) \in A} q_{(n,n')}^p \geq 0, \qquad (\epsilon_e^p) \qquad \forall p \in P,\ e \in E_p, \tag{4.3}$$

$$Cap_{(n,n')}^T - \sum_{p' \in P} q_{(n,n')}^{p'} \geq 0, \qquad (\phi_{(n,n')}) \qquad \forall p \in P,\ (n,n') \in A. \tag{4.4}$$

Our model incorporates a complex network topology which allows for routing of sales volumes along different paths and several nodes; we use the notion of path variables $q_{(n,n')}^p$ (Harker, 1986b). This concept allows us to map trade flows from mines to demand regions along several intermediary nodes.

Energy balance equations have to hold for mining regions $m \in M_p$:

$$s^p_m + \sum_{(n,m)\in A} q^p_{(n,m)} = \sum_{(m,n)\in A} q^p_{(m,n)} \qquad (\lambda^p_m) \qquad \forall p \in P,\ m \in M_p, \tag{4.5}$$

for export regions $e \in E_p$:

$$\sum_{(n,e)\in A} q^p_{(n,e)} = \sum_{(e,n)\in A} q^p_{(e,n)} \qquad (\lambda^p_e) \qquad \forall p \in P,\ e \in E_p, \tag{4.6}$$

and for demand regions $d \in D$:

$$\sum_{(n,d)\in A} q^p_{(n,d)} = x^p_d + \sum_{(e,n)\in A} q^p_{(e,n)} \qquad (\lambda^p_d) \qquad \forall p \in P,\ d \in D. \tag{4.7}$$

The objective function (4.1) and equations (4.2) to (4.7) define the maximisation problem Ω_p. In the case that the objective function P_p is concave, all constraints are convex, and all functions are continuously differentiable, the formulated optimisation problem can be represented by its first order optimality conditions. In this case, the first order derivatives constitute necessary-and-sufficient equilibrium conditions.

Producer Optimality Conditions

We develop the Lagrangian $\mathcal{L}$ of the original problem Ω_p. In the following, we derive the first order optimality conditions of $\mathcal{L}$. The first order partial derivative w.r.t. export volumes x^p_d between player $p \in P$ and $d \in D^-$ is given by

$$v_d(X_d) - \left(\lambda^p_d - \left(\frac{\partial v_d}{\partial x^p_d} + \frac{\partial v_d}{\partial X^-_d}\frac{\partial X^-_d}{\partial x^p_d}\right) x^p_d\right) t^{p\to d} \geq 0 \perp x^p_d \geq 0, \qquad \forall d \in D^-. \tag{4.8}$$

The first term is the price in node d. The second term gives the marginal cost of supply of player p to node d. The third term is the Cournot mark-up depending on the marginal change of consumer price if player p changes x^p_d marginally. We adjust prices by value added tax differences and royalties between different model regions by multiplying export prices with the term $t^{p\to d}$. In equilibrium, if $x^p_d \geq 0$, the achieved price of exports p_d has to offset marginal costs of supply to node d and the marginal price decrease caused by this export flow in d.

The Cournot player perceives that the demand function in d is downward sloping and thus can extract an oligopolistic producer rent. His sales decision for d also depends on his conjecture on how sales of competitors for d change, given a change in his sales:

$$\frac{\partial v_d}{\partial x^p_d} + \frac{\partial v_d}{\partial X^-_d}\frac{\partial X^-_d}{\partial x^p_d} = \frac{\partial v_d}{\partial x^p_d}(1 + r^{p\to d}). \tag{4.9}$$

$\frac{\partial v_d}{\partial x_d^p} = r^{p \to d}$ is the aggregate conjecture of player p on how export flows from all other players $p^* \in P^-$ change given a change in its own export trade volume to demand region d. For perfect competition, $r^{p \to d}$ equals -1 and for a Cournot-Nash equilibrium this term equals 0.[62]

P behaves as a welfare maximiser in his domestic national markets. First-order pricing conditions for P's supply x_d^p in domestic markets $d \in D_p$ are defined as:

$$v_d(X_d) - \lambda_d^p \geq 0 \perp x_d^p \geq 0, \qquad \forall d \in D_p, \tag{4.10}$$

which means that P is behaving as a price taker in its domestic markets.

Single mining regions are assumed to behave competitively, supplying at marginal cost levels plus scarcity rents for congested mining capacity

$$\frac{\partial C_m^p(s_m^p)}{\partial s_m^p} + \mu_m^p - \lambda_m^p \geq 0 \perp s_m^p \geq 0, \qquad \forall m \in M_p. \tag{4.11}$$

For the mine production cost C_m^p, we choose a function of production volume s_m^p according to Golombek et al. (1995). In their paper, the authors present a production cost function, for which the marginal supply cost curve has an intercept $\alpha_m \geq 0$, then follows a linear trend with slope $\beta_m \geq 0$ until production reaches almost the capacity limit. As soon as the supply level approaches production capacity limits, the marginal costs can increase exponentially depending on a parameter $\gamma_m \leq 0$. The economic intuition behind this functional form for marginal costs is that prices during periods with higher demand are in reality often set by older mine deposits. As geological conditions decline, these mines face significantly higher costs and have to reduce their production output due to geological constraints and limited reserves. These high-cost mine fields serve as spare capacity during demand peaks and reduce their output if demand declines.

The strictly convex and continuously differentiable marginal supply cost function $\frac{\partial C_m^p(s_m^p)}{\partial s_m^p} = c_m^p : [0, Cap_m^M) \mapsto \mathbb{R}^+$ for player $p \in P$ and mine $m \in M_p$ is defined as:

$$c_m^p(s_m^p) = \alpha_m + \beta_m s_m^p + \gamma_m \ln\left(\frac{Cap_m^M - s_m^p}{Cap_m^M}\right), \qquad \alpha_m, \beta_m \geq 0,\ \gamma_m \leq 0. \tag{4.12}$$

Price efficiency conditions have to hold for every transport connection $(n, n') \in A$. Hence price efficiency requires that marginal costs of supply λ_n^p and $\lambda_{n'}^p$ only differ by transport costs and a possible mark-up for scarcity rents in the case of congested transport capacity $\phi_{(n,n')}$ if $q_{(n,n')}^p \geq 0$.

$$\lambda_n^p + c_{(n,n')}^T + \phi_{(n,n')} - \lambda_{n'}^p \geq 0 \perp q_{(n,n')}^p \geq 0, \qquad \forall n, n' \in M_p \cup D \ \wedge\ (n, n') \in A. \tag{4.13}$$

[62]Kolstad and Burris (1986) elaborate more on this topic. Such games were applied in equilibrium energy market modeling e.g. by Graham et al. (1999), Chen et al. (2006), or Lise and Krusemann (2008).

Similar conditions hold for transport connections going out of export terminals but include an additional scarcity mark-up variable for congested export terminal capacity ϵ_e^p,

$$\lambda_e^p + c_{(e,n)}^T + \phi_{(e,n)} + \epsilon_e^p - \lambda_n^p \geq 0 \perp q_{(e,n)}^p \geq 0, \qquad \forall e \in E_p, \wedge (e,n) \in A. \tag{4.14}$$

Market Clearing Conditions

In addition to the derived first order optimality conditions, we assume that there is no market power on the demand side and that all markets in demand regions $d \in D$ are cleared when players have decided on their strategies. We choose a linear, strictly decreasing demand function $v_d(X_d) : \mathbb{R}^+ \mapsto \mathbb{R}^+$ of the form $v_d = a_d + b_d X_d$. The slope b_d is defined as $b_d = \frac{v_d^{ref}}{X_d^{ref}} \frac{1}{\sigma_d}$, and the intercept a_d can be written as $a_d = v_d^{ref} - b_d X_d^{ref}$, where σ_d, v_d^{ref} and X_d^{ref} are the demand elasticity, reference price, and total reference consumption in demand region d, respectively. This leads to the following inverse demand function:

$$v_d = v_d^{ref} + \frac{1}{\sigma_d} \left(\frac{\sum_{p' \in P} x_d^{p'}}{X_d^{ref}} - 1 \right), \qquad v_d \ (free) \qquad \forall d \in D. \tag{4.15}$$

We can now calculate:

$$\frac{\partial v_d}{\partial x_d^p} = \frac{p_d^{ref}}{X_d^{ref}} \frac{1}{\sigma_d} = b_d. \tag{4.16}$$

Inserting (4.16) into the profit maximisation condition (4.8) yields:

$$v_d(X_d) - \left(\lambda_d^p - \frac{p_d^{ref}}{X_d^{ref}} \frac{1}{\sigma_d} (1 + r^{p \to d}) x_d^p \right) t^{p \to d} \geq 0 \perp x_d^p \geq 0 \qquad \forall d \in D. \tag{4.17}$$

If we bundle the equations (4.15) with the first order conditions (4.17), (4.11), (4.13), (4.14) and capacity constraints (4.2) to (4.7) for all producers $p \in P$, the unique solution to this set of (non)linear inequalities yields the equilibrium for the market. The resulting system of inequalities is known as a mixed complementarity problem. This problem is implemented in GAMS and is solved using the PATH solver (Ferris and Munson, 1998).

4.3.2 Model Parametrisation

For our analysis, we have to specify the model parameters for costs, capacities, and demand.

Our assumptions on reference volumes, and for price elasticities of coal demand in Europe, are explained in detail in Trüby and Paulus (2012)[63]. Demand elasticities for other regions are based on a broad literature review of econometric analyses on interfuel substitution. While methodological approaches as well as the age of the reviewed articles differ, all authors agree that price elasticity of steam coal demand is inelastic $\mid \sigma \mid < 1$. In the presented paper, we assume a price elasticity of steam coal demand for -0.3 for the other world regions besides Europe.

Information on costs and capacities in the steam coal market is only available from a multitude of heterogeneous sources. We use the extensive steam coal market database in this analysis that has already been presented and used in two of our former analyses Paulus and Trüby (2011) and Trüby and Paulus (2012)[64].

We consider it crucial to capture not only isolated steam coal trade market economics but also the interdependencies between the large domestic markets and the trade market. Therefore, we have implemented a detailed network topology consisting of several dozen mining regions, export terminals, and demand regions (see table 4.4). Note that our model includes the two largest domestic markets, China and the US, which together account for about 65% of global hard coal production and about 66% of global consumption. Other major domestic markets are Russia and India, which have also been taken into account.

4.3.3 Market Structure Scenarios

We simulate the global steam coal trade for 2008 under four different assumptions on market conduct and the nature of Chinese export quotas to test our hypotheses:

Perfect competition without Chinese export quota: This scenario assumes that all producers and consumers act in a competitive manner. We further assume no Chinese export quotas in this scenario to assess how unconstrained Chinese export

[63] In this article, we use existing large-scale power sector dispatch models for Europe and iteratively test a high number of steam coal price points. The model returns a minimum cost power plant dispatch as well as steam coal consumption. The results show that the steam coal demand elasticity in the European power sector was relatively low, -0.43 in 2008.

[64] Relevant publications on steam coal markets are available from public institutions like the IEA (2009) or the EIA (2006, 2010a,b). More specifically, comprehensive information can be found in the published reports of the IEA Clean Coal Center, e.g.: Baruya (2007, 2009), Minchener (2004, 2007), and Crocker and Kowalchuk (2008). Furthermore, Ritschel (2010) and Schiffer and Ritschel (2007) depict recent developments in the hard coal markets. Further publications include analyses from employees working for international utilities like Bayer et al. (2009) and Kopal (2007). Industry yearbooks provide useful information as is the case for China (CIRI, 2007, NBS, 2008). National statistics bureaus and mineral ministries provide high quality information, for example ABARE (2008) and ABS (2006). Not mentioned are a larger number of coal company annual reports as well as information based on expert interviews. Information on average energy content is based on IEA (2009), Ritschel (2009a) and BGR (2008). For Australia, ABS (2006) delivers detailed information and Baruya (2007) compares different mining input factor structures on the global scale. Furthermore, our analysis is based on several extensive research projects of Trüby (2009) and Eichmüller (2010) at the Institute of Energy Economics at the University of Cologne.

Table 4.4: Model topology

Mining regions & export terminals[a]		Demand regions	
Australia	5	**Russia**	4
South Africa	3	**U.S.**	7
Indonesia	2	**China**	8
Russia	8	**India**	3
Colombia	2	**Poland**	2
Venezuela	2	Europe	3
Vietnam	2	Japan	1
U.S.	6	Korea (S.)	1
China	10	Taiwan	1
India	6	Other Asia	1
Poland	3		

[a]Bold case indicates countries with large domestic steam coal markets which have been explicitly modelled.

patterns would have looked and how they would have influenced the steam coal market.

Perfect competition with Chinese export quota: This scenario also assumes perfectly competitive behaviour of market players but incorporates the Chinese export quota as a fixed export restriction. Thus, we assume that the export quota was not necessarily set under strategic welfare maximisation objectives, but could exist due to other political objectives like the conservation of domestic resources. With this scenario, we can test for the competitiveness of the global steam coal market.

Indonesian monopoly with Chinese export quota: In this scenario we assume that Indonesia, the largest exporter, acts as a strategic national player facing a competitive fringe of other market players. The Chinese export quota is modelled as a fixed export restriction for the Chinese player. This scenario lets us test for non-competitive behaviour of Indonesia.

China - Indonesia duopoly: Besides their large market shares, Indonesia and China face special political, geographical, and institutional characteristics which could potentially support non-competitive behaviour. We therefore model both countries as non-cooperative strategic players. With this scenario we can investigate if Chinese export quota setting is consistent with a profit maximising Cournot strategy, together with Indonesian market power.

4.3.4 Model Validation Using Statistical Measures

We assess the forecasting abilities of the model by comparing trade flows as well as trade flow shares as a fraction of total trade with the actual values in 2008. We also validate model prices with real price data.

In order to validate which of the market conduct scenarios fits the observed data best, we employ a series of statistical techniques. Using common parametric tests in such a setup would lead to the violation of several assumptions, most importantly, that the error term is normally distributed. Alternatively, it is possible to use non-parametric tests which do not make the same assumptions on distributions. We use two such tests to validate our results: the Wilcoxon-Rank-Sign test and Spearman's rank correlation coefficient test.

The Wilcoxon-Sign-Rank test evaluates on the basis of a paired sample the signed-rank correlation between the sets (Wilcoxon, 1945). We employ this test on the modelled trade flow share matrix M and the observed trade flow share matrix O. (m_{pd}, o_{pd}) are the corresponding modeled and observed trade flow shares for all $p \in P$ and $d \in D$. The null hypothesis is that the model results predict actual trade.

An alternative test, which is also distribution-free, is Spearman's rank correlation coefficient test. Similar to Abbey and Kolstad (1983) and Graham et al. (1999), we try to find if the observed trade shares and the error between predicted and observed values has no rank-correlation; this would indicate that there is no association between the error terms and the actual values. The regression of the observed values o_{pd} against the predicted values m_{pd} yields the regression equation:

$$o_{pd} = \alpha + \beta m_{pd} + \hat{u}_{pd}, \qquad \forall p \in P,\ d \in D$$

If our model perfectly simulated each trade flow share, then β would equal 1 and α would equal 0. To test for these parameter values, we let $\hat{u}_{pd} = o_{pd} - m_{pd}$ and test the extent of rank correlation between o_{pd} and $\hat{u}_{pd}$ by applying Spearman's rank correlation coefficient. The null hypothesis is that there is no correlation between observed values and the error term between modelled and actual values or, equivalently, that the model predicts the observed market outcome.

Furthermore, we also employ statistics without testing for interference: the Theil inequality coefficient is the root mean squared error of two datasets scaled to the $[0, 1]$ interval (Theil, 1966). It measures how distant both datasets are from each other in a statistical sense. In case of the Theil coefficient equaling zero, the modelled trade shares are exactly the same as the actual ones. Therefore, the lower the Theil coefficient, the better the model suits as an indicator for the real market. Further information can be obtained by calculating the covariance proportion, the variance proportion, and the bias proportion of the mean squared error (MSE). A good quality forecast should have a MSE which is mostly explained by the unsystematic error. In this case, the bias and the variance proportion should be close to zero and the covariance proportion close to one.

TABLE 4.5: Comparison of statistics of actual and modelled trade flows in 2008

Test statistics[a]	Market structure				Actual market
	PC w/o export quota	PC w. export quota	Indonesia monopoly w. export quota	China - Indonesia duopoly w/o export quota	
$\rho_{Spearman}$	0.328**	0.259**	0.186	0.162	
$z_{Wilcoxon}$	2.53**	1.80*	1.17	0.62	
Theil	0.42	0.352	0.214	**0.152**	
Error term decomposition:					
-Covariance proportion	0.934	0.848	0.835	**0.935**	
-Variance proportion	0.078	0.165	0.174	**0.063**	
- Bias proportion	0.002	**0.002**	0.007	0.018	
RMSPE [%]	23.5	16.9	11.6	**7.9**	
Results on market size in Mt					
Total trade volume	732	659	645	**628**	608

[a] $\rho_{Spearman}$ is the Spearman rank correlation coefficient, $z_{Wilcoxon}$ is the statistic for the Wilcoxon sign rank test, Theil is the Theil inequality coefficient, and U^c is its covariance proportion. Bold case indicates the lowest Theil statistic or that the covariance (variance,bias) proportion is closest to one (closest to zero). The same holds for the root mean-squared percentage error (RMSPE). The null hypothesis for both tests is that the model can predict trade in 2008.
*Significant on the 90% level. Critical values: $\rho_{Spearman}$=0.213 and | $z_{Wilcoxon}$ |=1.650.
**Significant on the 95% level. Critical values: $\rho_{Spearman}$=0.253 and | $z_{Wilcoxon}$ |=1.960.
***Significant to the 99% level. Critical values: $\rho_{Spearman}$=0.329 and | $z_{Wilcoxon}$ |=2.576.
Critical values are based on Zar (1972) and McCornack (1965).

4.4 Results

Table 4.5 reports results on statistical inference, as well as on several other statistics in the four simulated scenarios. Both perfect competition assumptions are rejected by the Wilcoxon Sign-Rank test on the 90% confidence level (95% level in the scenario without export quota). Neither non-competitive scenarios can be rejected at typical confidence levels. The Spearman rank correlation test rejects the two perfect competition scenarios as statistically significant estimators for the actual market outcome on the 95% level. Again neither non-comeptitive scenarios can be rejected at typical confidence levels.

The other statistics further confirm the non-competitive setups: the Theil inequality coefficient as well as the RMSPE are far lower than in the perfect competition scenarios. However, for both statistics the *China - Indonesia duopoly* scenario even outperforms the *Indonesia monopoly* scenario. The values for covariance proportion and for the variance proportion are also the best in the *China - Indonesia duopoly* setup. The bias proportion is the lowest (best) in the *perfect competition with export quota* scenario. Nevertheless, the bias proportion is also relatively low in the *China - Indonesia duopoly* scenario with 2%.

The international seaborne trade market size is an endogenous variable to the model as we account for interactions of the trade market with the domestic markets. We therefore compare how good the model results for the total trade market volume fit the actual figures. In the *perfect competition scenario without export quota*, the simulated trade market volume was 20% larger than the actual market size in 2008. In this scenario, Indonesia and especially China significantly increase their exports to cover the high international demand in the year 2008. This leads to a drastic increase in traded steam coal volumes in the Pacific area. In the *perfect competition with export quota* scenario, Chinese export volumes are constrained which leads to a lower total trade market volume. The *China - Indonesia duopoly* setting sees the best market volume fit with the trade market being only 4% larger than in reality. China, as the largest producer, and Indonesia, as the largest trade market exporter, withhold volumes in a Cournot manner. Under the Cournot assumption, simulated Chinese exports (43.3 Mt) almost excatly meet the export quota (47.8 Mt). This means that the Chinese export policy was consistent with a Cournot-Nash strategy[65] in 2008. Additionally, the Cournot competition leads to a diversification of Chinese exports similar to reality with Japan, South Korea, and Taiwan being the main destinations.[66] However, in all scenarios in which China acts competitively, China exports exclusively to South Korea.

A similar observation can be made for Indonesia: Indonesian supply is similarly diversified as actual values in both non-competitive scenarios. In the *China - Indonesia duopoly* scenario, simulated Indonesian exports (160.4 Mt) almost match actual values (157.4 Mt, energy-adjusted). This is in contrast to the perfect competition scenarios, where Indonesia's absolute exports are more than 30 Mt higher. Also, in the competitive scenarios, exports from Indonesia to China are strikingly higher than in reality. In general, the China - Indonesia duopoly setup clearly outperforms both perfect competition scenarios. The *China - Indonesia duopoly* setup also performs better than the *Indonesia monopoly with Chinese export quota* scenario in all statistics except for the bias proportion. However, neither non-competitive scenarios can be rejected as predictors of actual market outcomes.

A further relevant indicator to analyse model forecasting quality are prices. The RMSPE for the *perfect competition without export quota (with export quota)* scenario is 21.7% (18.7%). For the *Indonesia monopoly with Chinese export quota* scenario the RMSPE is 4% and for the *China - Indonesia duopoly* scenario 3.6%. Figure 4.1 plots

[65] Of course this is no hard evidence for China being a strategic player.

[66] Trade flows are more diversified in the non-competitive equilibrium compared to the perfectly competitive market outcome. In the Cournot game, firms with higher marginal costs of delivery, e.g. due to high transport costs to distant demand regions, have lower market shares in the respective demand regions. Lower market shares however imply higher perceived marginal revenues for a player. Since the Cournot oligopolists equate marginal revenues to marginal costs, the higher perceived marginal revenue may justify trade with regions that would, cost-wise, not occur in a perfectly competitive market. For a more sophisticated analysis of this issue refer to Brander (1981) and Brander and Krugman (1983).

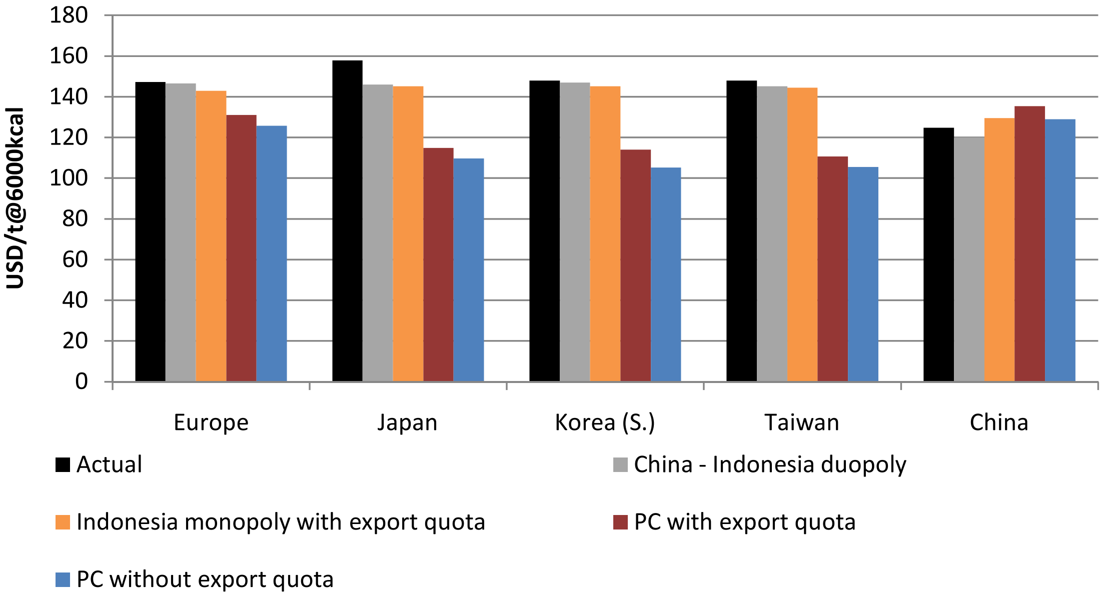

FIGURE 4.1: Comparison of actual and simulated prices for important import regions

actual against simulated prices. We observe that prices in the perfect competition setups are approximately 15-20 USD/t lower in Europe and up to 40 USD/t lower in the main Asian importing regions than observed prices. Simulated import prices in China are higher than in reality. Furthermore, we see that prices in both perfect competition scenarios do not differ greatly, even though Chinese exports are 70 Mt lower since Indonesia is still exporting above its observed values.

Model prices for both non-competitive scenarios fit the observed values better. While simulated import prices meet the actual European price levels, this scenario also fairly accurately replicates actual prices in the Asian import regions. The best price fit for China has the *China - Indonesia duopoly* scenario: here, the Cournot mark-up of Chinese exports leads to a larger price difference between other Asian import regions and Chinese domestic demand regions which basically protects the Chinese coal market and reduces coal consumer prices.

Simulated Japanese import prices may not be completely explained even in the *China - Indonesia duopoly* setup[67]. Apart from these deviations, both non-competitive scenarios deliver the most accurate reproduction of actual import prices.

Considering the actual and simulated trade flow matrices, the perfect competition setups feature a less diversified structure of supply than the non-competitive scenarios (see table C.1 in appendix C).

[67]Besides statistical errors and differences in energy-mass conversions, coal quality is a factor which may let model results deviate from real trade patterns. Especially in Japan, newer coal-fired power plants are highly efficient but very limited in the types of steam coal that they can use for generation. Coal specifications on sulphur, ash content, moisture, and volatile matter are important determinants for coal-fired power plants. This dependence may sometimes lead to a certain price inelasticity of demand for certain coal types. Trade patterns and price effects caused by coal quality requirements beyond energy content are not explicitly modelled and beyond the scope of this analysis.

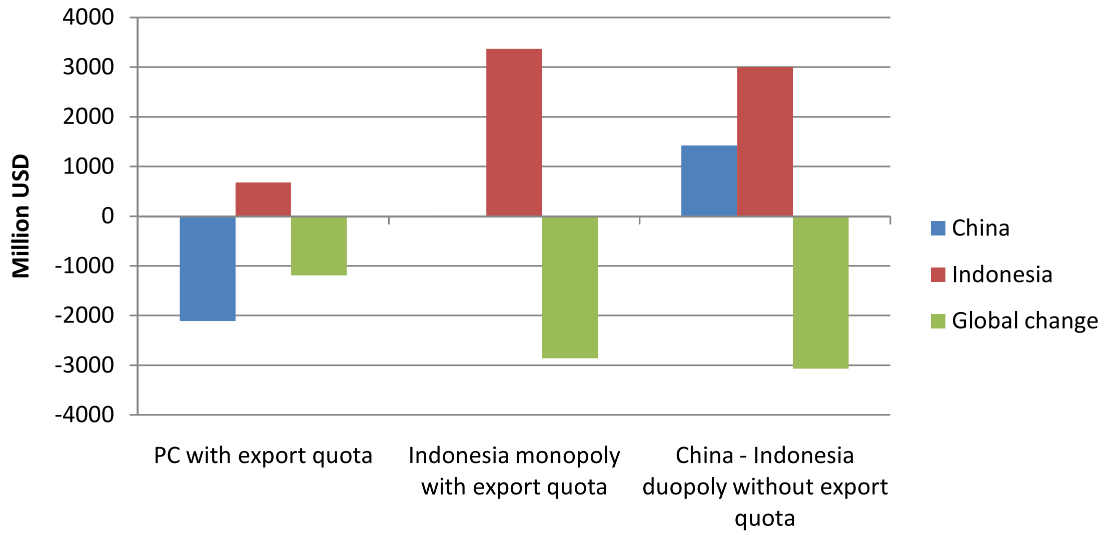

FIGURE 4.2: Welfare effects in the investigated scenarios (horizontal lines represents the perfect competition scenario without export quota).

Economic theory suggests that perfect competition, *ceteris paribus*, leads to a higher total welfare compared than a scenario with imperfectly competitive market behaviour. The baseline in figure 4.2 is therefore the *perfect competition without Chinese export constraints* scenario.

In the *perfect competition scenario with Chinese export quota*, China accrues less welfare due to its export restriction. Indonesian rents increase to a certain extent due to slightly higher world market prices. In the *Indonesia monopoly* scenario, Indonesian rents increase by around 3 bn $ as the withholding of Indonesian supply on top of the Chinese export quota increases consumer prices significantly. In this scenario, Chinese welfare effects are close to zero, as positive revenue effects due to higher consumer Asian prices and negative effects due to the export quota cancel each other out. Overall global welfare effects are negative due to lower consumer rents especially in the main Asian importing nations of Japan, Taiwan, and South-Korea, but also in Europe.

In the *China - Indonesia duopoly* setup, China accrues additional rents[68] of 1.4 bn USD while oligopolistic rents of Indonesia decrease slightly. Chinese rents increase as exports are distributed with regard to profit maximisation targets also supplying Japan and Taiwan. Consumer prices for steam coal in China are lower compared to the *Indonesia monopoly* scenario, which positively affects Chinese consumer rents.

Summarising our findings, we conclude that hypothesis H1 (perfect competition) can clearly be rejected as prices and trade flow patterns cannot explain the real market outcome. Neither non-competitive scenarios can be rejected as predictors of actual trade. Indonesian and Chinese exports are more accurately distributed compared to their counterparts in the perfect competition setup. Furthermore, total Indonesian export

[68]We also account for welfare changes in the domestic Chinese steam coal market.

volumes fit better in the non-competitive setups. Of the two non-competitive setups, the *China - Indonesia duopoly* scenario performs slightly better in several statistics, trade flows, and prices. Interestingly, the Cournot-Nash strategy for China reproduces almost exactly the Chinese export quota. Additionally, positive welfare effects for China are the highest in this setup.

Therefore, we cannot reject either H2 (Indonesian monopoly with Chinese export quota) and H3 (China - Indonesia duopoly). However, the *China - Indonesia duopoly* outperforms the *Indonesia monopoly* scenario in seven of eight statistics. The duopoly scenario also shows the highest welfare accruement for China. In light of the proactive national resource-security policy in China, one may therefore even support the acceptance of H3.

4.5 Conclusions

Due to the increasing demand for mineral resources in recent years, several resource-rich nations have reassessed and adjusted their national resource policies. They have applied different instruments of strategic trade policy, such as export quotas. However, it may not always be clear if these resource policies serve conservation of natural resources or maximisation of national rent inflows from resource exports. We empirically investigated this question for the case of the global steam coal market by testing for non-competitive market conduct on the part of China and Indonesia. Both countries have implemented or significantly realigned their coal export strategies in recent years.

For this purpose, we developed a spatial conjectural variations model which allowed us to model individual nations as strategic players, maximising their domestic welfare as well as their rents from exports subject to a Cournot-Nash strategy. We described how China and Indonesia could potentially exercise market power in reality and derived two non-competitive market conduct setups from this investigation. We applied several statistical tests to avoid arbitrary modelling results. Therefore, we come to the conclusion that we cannot reject the two non-competitive market setups as predictors of the actual steam coal market in 2008. Test statistics indicate that the *China - Indonesia duopoly* scenario is the better predictor than the *Indonesia monopoly* scenario. We also found that Chinese export quotas are consistent with simulated Chinese export volumes under a Cournot-Nash strategy, which gives further strength to our hypothesis regarding strategic behaviour of China.

We find that it is crucial to account not only for export markets, but also for the domestic markets, respecting their interactions and feedbacks if one analyses potential market power of strategic national players. If export market prices rise high enough, a national player will redirect domestic volumes to the export market as marginal revenues are higher. Therefore one may expect that the large Chinese supply compensates for any international coal demand shock or export capacities withheld. However, our analysis shows that this is not the case due to applied Chinese strategic trade policies.

These findings yield implications for policy makers in nations depending on coal imports: future supply and prices for internationally traded coal might possibly not be as cheap, stable, and secure as perceived by most if emerging Asian nations increasingly pursue their national resource export strategies. This could make a re-evaluation of the future role of coal in energy consumption of such countries necessary, as especially cost-competitiveness and abundance have often been named as the main advantages of coal compared to other energy sources.

On a more general level, our findings indicate that the increasing influence of non-Western countries on world resource markets might change the current world trade paradigm. Strategic trade policy might become important also for markets which have been perceived as competitive before.

Possible future research could extend the analysis of strategic national players to account for the complete fuel complex or to internationally traded non-energy minerals. A multilateral market power analysis accounting for market power on the importer's side may also be an appropriate research venue.

Chapter 5

Coal Lumps vs. Electrons: How Do Chinese Bulk Transport Decisions Affect the Global Steam Coal Market?

5.1 Introduction

Steam coal[69] sourcing and costs have not presented a real challenge in the past few decades. However, this situation could change. The center of gravity and price setting in the global steam coal trade market has been shifting to Asia since 2005 (Ritschel, 2009a). An important driver for the future evolution of steam coal market economics will be China as Chinese demand today already makes up 45% of the global market volume[70]. Well-established energy outlooks project that Chinese demand might rise by 80% to 130% by 2035 compared to 2007 levels (EIA, 2010b).

In addition to the challenges of providing an additional 2 billion tonnes of steam coal mining capacity until 2030 and significantly increasing exploration efforts to generate proven, marketable reserves, the main challenge is that steam coal supply and demand are spatially separated in China (Minchener, 2007). The majority of the country's coal reserves lie in the North-central Chinese provinces of Shaanxi, Shanxi, and Inner Mongolia, as well as far in the West, in the province of Xinjiang. Inland transport distances from these regions to the coastal demand centres around Beijing, Hong Kong,

[69] Steam coal is hard coal of bituminous and sometimes subbituminous or anthracite quality which is typically used in electricity generation.

[70] The global steam coal market is defined as total global steam coal production and demand worldwide, including domestic markets. The global steam coal trade market on the other hand consists of the internationally traded volumes (mostly by sea transport) which only make up a small fraction of the global market. The global steam coal trade market volume was 658 Mt while the global steam coal market volume was 5000 Mt in 2009 (IEA, 2009).

and Shanghai total up to 3500 km. Coal transport in China mainly takes place by rail, river barges, and coastal shipping, which significantly increases costs of supply to the coastal demand centres. Approximately 60% of Chinese coal output was hauled via railway along distances of more than 500 kilometers to coal-fired power plants in 2005 (CIRI, 2006). Transport costs make up more than half of the delivered costs for domestic coal in the Southern provinces. Chinese demand centres are located along the coast and have the opportunity to procure steam coal volumes on the global trade market. Thus, high domestic transport costs combined with rising mining costs have recently led to an increase in steam coal imports (Ritschel, 2010).

Future Chinese steam coal demand can be satisfied either through additional domestic steam coal production or by increasing steam coal imports. One important driver for determining the Chinese supply mix is the future domestic transport costs between the coal-bearing regions in North-Central China and the coastal areas.

The primary energy carrier coal can be transported via railway or can be converted on-site to electricity which is then transported via HVDC lines to the main consuming regions. Currently, China mainly relies on railway expansion projects to significantly increase its coal transport capacity (Minchener, 2004, Sagawa and Koizumi, 2007) from the West to the Eastern regions. Even though China has been able to rapidly expand its railway infrastructure during recent years to cope with the majority of the rising coal transport, railway transport is comparatively expensive (Minchener, 2004).

Another transport option for China is investment into large-scale HVDC transmission in combination with mine-mouth coal-fired power plants in the North-central coal-bearing provinces. Such an energy transport system could significantly reduce variable transport costs and could supply coal-based energy to the Chinese coastal demand centres. Unfortunately, large-scale deployment has thus far been hindered by weak central energy planning institutions as well as regulatory schemes that provide few incentives for Chinese grid companies to invest in power transmission (Fedor, 2008, MIT, 2007).

Nevertheless, the need for a coherent domestic energy transport strategy remains pressing, particularly regarding the continuing consolidation process in the Chinese coal industry (Peng, 2011). Initiated by national reform efforts to enhance work safety and efficiency of the entire industry, recent policy implementation has led to the closing or merging of small, inefficient, and unsafe coal mines, thus improving economies of scale (ESMAP, 2008, NDRC, 2007). Consequently, the share of small coal mines in total domestic production dropped significantly from 19.9% (342Mt) in 2003 to 2.1% (55Mt) in 2008 (CIRI, 2008). In addition to the permanent increases in national coal trade volume in recent years, this might have proven to be an additional burden to the prevalent energy transport system, since the restructuring process results in a concentration of production in remote regions in the North and North West of China (Lester and Steinfeld, 2006). Taking these implications of the policy of increased efficiency in the coal industry into account, setting up HVDC transmission lines could be regarded as a logical extension in an overall strategy for improvement of energy efficiency.

The analysis focuses on the two effects of the two outlined bulk energy transport investment strategies in China: firstly, how is the future Chinese steam coal supply mix affected by different bulk energy transport modes? Secondly, what are the implications of the change in the Chinese coal supply mix for the world steam coal market? Hence, the presented paper will look at the future Chinese coal supply mix, at the global long-run marginal costs of steam coal in China and several important world market regions, at the worldwide mining investments and utilisation, as well as at the global welfare effects. To analyse these aspects, a spatial equilibrium model which minimises total costs of global steam coal demand coverage is developed and presented. This global modelling approach makes it possible to obtain answers to the proposed research questions, including feedbacks and interdependencies between worldwide market actors. The model is validated for the reference years 2005 and 2006. Then, two scenarios for possible future transport infrastructure investment decisions in China are investigated: one scenario assumes continued investment in railroad transport to move coal energy to the demand centres. The second scenario assumes large-scale investment in HVDC transmission lines combined with mine-mouth coal-fired power plants and transmission of electricity to the demand hubs. Then steam coal flows and marginal supply cost patterns for both scenarios are projected up to 2030.

The remainder of the presented paper includes seven sections: after an outline of the relevant literature regarding supply cost modelling and coal market analyses in section 5.2, the current situation in the steam coal trade market will be briefly described in section 5.3. Then, the model is introduced in section 5.4. Section 5.5 describes the underlying dataset. Section 5.6 depicts the scenario assumptions, and section 5.7 reports model results. Section 5.8 concludes the paper.

5.2 Related Literature

The most obvious characteristic of the steam coal world market is its spatial structure. Steam coal demand regions are not necessarily at the location of the coal fields. Coal fields are dispersed widely over the globe and internationally traded coal is usually transported over long distances to satisfy demand.

Researchers have scrutinised the economics of such spatial markets in depth. In an early approach, Samuelson (1952) combined new insights from operations research with the theory of spatial markets and develops a model based on linear programming to describe the equilibrium. Using marginal inequalities as first-order conditions, he models a net social welfare maximisation problem under the assumption of perfect competition. Based on Samuelson's findings, Takayama and Judge (1964) developed an approach that uses quadratic programming. Moreover, they present algorithms that are able to efficiently solve such problems also in the multiple commodity case. Harker (1984, 1986a) is particularly concerned with imperfect competition on spatial markets. He extends the monopoly formulation as presented by Takayama and Judge to a Cournot formulation which yields a unique Nash equilibrium and suggests algorithms to solve the generalised problems. Yang et al. (2002) develop conditions for the Takayama-Judge spatial equilibrium model to collapse into the classic Cournot model. They demonstrate that, in the case of heterogeneous demand and cost functions, the spatial Cournot competition model is represented by a linear complementarity programme (LCP).

One research strand of steam coal market economics has focused on analysing market conduct either in the global trade market or in regional markets. Abbey and Kolstad (1983) and Kolstad and Abbey (1984) analysed strategic behaviour in the international steam coal trade in the early 1980s. In both articles, the authors' model is an instance of a mixed complementarity problem (MCP). These models are based on the Karush-Kuhn-Tucker conditions and a number of market clearing conditions. In addition to perfect competition, they model different imperfect market structures. Labys and Yang (1980) developed a quadratic programming model for the Appalachian steam coal market under perfectly competitive market conditions including elastic consumer demand. They investigate several scenarios with different taxation, transport costs, and demand parameters and analyse the effect on steam coal production volumes and trade flows. Haftendorn and Holz (2010) developed a model of the steam coal trade market in which selected exporting countries behave as Cournot players in a first scenario and as competitive players in a second scenario. They found no evidence for exporting countries having exercised market power in the years 2005 and 2006.

Literature on how bulk energy transport modes influence underlying resource or electricity markets is scarce at best. However, related analyses of such effects on a regional level exist: Quelhas et al. (2007a) and Quelhas et al. (2007b) developed a multi-period network flow model for a one-year time period in the integrated energy system in the United States. They modelled system-wide energy flows, from the coal and natural gas suppliers to the electric load centres and identify that actors can increase energy system efficiency if they overcome informational and organisational barriers. Empirical studies include for example Bergerson and Lave (2005), who investigated in a case study the lifecycle costs and environmental effects of transporting coal-based energy between the Powder River Basin (Wyoming) and Texas. They discovered that, depending on energy volumes and utilisation of existing railway infrastructure, HVDC electricity transmission is a cost efficient option for long distance transport. Oudalov and Reza (2007) described a bulk energy transport model for technology assessment and comparative analysis of bulk energy transport systems. They concluded that for long-distance transport early conversion of coal into electricity and transmission with HVDC technologies demonstrates significant improvements over conventional overland transport. There has been no publication so far on how large-scale infrastructure investments involving a combination of HVDC lines and mine-mouth power plants influence the coal supply mix. None of the mentioned articles venture into the feedbacks of coal energy transport decisions in China and the global steam coal market including feedbacks of the global market. The goal of the presented paper is to understand how different future bulk energy transport configurations for China could shape the steam coal supply mix and market economics worldwide.

5.3 Structure of the Global Seaborne Steam Coal Trade

Considerable changes have occurred during recent years in the market for steam coal. The global seaborne hard coal trade market amounted to 839 Mt in 2008 – an increase of 58% compared to the market volume in the year 2000. The majority of global seaborne hard coal trade consists of steam coal (639 Mt in 2008). The seaborne trade market can be divided into the Pacific market region and the Atlantic market region[71].

The Pacific market basin saw a large increase not only in domestic production and demand but also in seaward traded volumes (table 5.1). This region has been surpassing the Atlantic basin in terms of relative market size growth during the last few years. On the supply side, Indonesia and Australia especially have significantly increased their exports between 2000 and 2008. New players on the demand side include India and recently China, whose import volumes are growing rapidly.

TABLE 5.1: Major players in the Pacific basin in 2008 in Mt

Country	Production	Consumption	Import	Export	Net-Export
Indonesia	214.9	41.9	0	173	173
Australia	185.3	70	0	115.3	115.3
Vietnam	39.9	19.9	0	20.6	20.6
PR of China	2334	2340.1	34.2	42.7	8.5
India	461.9	491.7	30.9	1.1	-29.8
Taiwan	0	60.2	60.2	0	-60.2
Korea, South	2.8	80.9	75.5	0	-75.5
Japan	0	128.2	128.2	0	-128.2

Source: IEA (2009).

The Atlantic market region is dominated by three large net exporters, Colombia, Russia, and South Africa (table 5.2). The U.S. have been a swing supplier in the Atlantic basin, and mid- to high-cost U.S. mines have been marginal suppliers for Europe in

[71]From a market integration perspective, the steam trade coal market can be considered well integrated (Li, 2008, Warell, 2006). Yet, this labeling is used in a qualitative sense to better structure our analysis of market actors.

recent years (Trüby and Paulus, 2010). Main net importers are mostly found in Europe, with the United Kingdom and Germany at the top. The overall demand for steam coal is likely to stagnate or slowly decline due to carbon emission restrictions and public opposition. The goal to phase out of subsidised coal mines (mostly in Germany and Spain) by 2018 and the stagnation in Polish and British coal production will counter or even overcompensate for this effect and will most likely expose Germany, Poland, and other Eastern European nations even more to procurements from the world trade market (IEA, 2009, Ritschel, 2009a).

Table 5.2: Major players in the Atlantic basin for 2008 in Mt

Country	Production	Consumption	Import	Export	Net-Export
Colombia	77.3	3.7	0.0	73.6	73.6
Russia	181.9	121.9	25.8	85.8	60.0
South Africa	234.2	172.9	2.9	61.3	58.4
Venezuela	8.8	2.4	0.0	6.4	6.4
United States	949.2	937.1	29.3	35.1	5.8
Brazil	0.2	6.6	6.4	0.0	-6.4
Denmark	0.0	7.1	7.6	0.2	-7.4
Netherlands	0.0	8.3	14.7	6.5	-8.2
Israel	0.0	12.8	12.8	0.0	-12.8
France	0.3	11.9	14.0	0.2	-13.8
Turkey	1.0	16.0	14.9	0.0	-14.9
Spain	7.3	20.8	17.6	1.8	-15.8
Italy	0.1	19.2	19.0	0.0	-19.0
Germany	8.6	45.3	36.9	0.6	-36.3
United Kingdom	16.2	50.2	37.4	0.4	-37.0

Source: IEA (2009).

5.4 The Model

The global steam coal market is modelled as a spatial and intertemporal equilibrium model. There are three types of model actors: mine owners, port operators, and coal consumers. Nodes representing port facilities, mining regions, and demand regions are assigned to each actor[72]. The nodes are interconnected by arcs representing inland transportation and sea routes. It is assumed that there is perfect competition between all actors in the market and that all regional markets are cleared in every period. Mine owners and port operators decide on optimal levels of production, transport, and investments in capacity. Transport cost fees represent haulage tariffs which cover full costs[73]. The global steam coal market may be considered competitively organised in the years

[72]Besides the trade market, domestic markets in China and the U.S. with their respective mining regions and demand regions are also modelled.

[73]In China for example, fees of state-operated railway companies include charges for the *Railway Construction Fund* which contribute to investment costs for future railway projects.

2005 and 2006 as well as integrated[74]. Although there may be phases of oligopolistic conduct, coal markets are generally contestable in the long-run due to the geographical dispersion and abundance of the resource.

5.4.1 Notation

In this section, the sets, parameters, and variables used in the model formulation are described. The time horizon of the model $T = \{2005, 2006, \ldots, t, \ldots, 2040\}$ includes one-year time periods from 2005 until 2015 and five-year time periods from 2015 to 2040.[75] The model consists of a network $NW(N, A)$, where N is a set of nodes and A is a set of arcs between the nodes. The set of nodes N can be divided into three subsets $N \equiv P \cup M \cup I$, where $m \in M$ is a mining region, $p \in P$ is an export terminal, and $i \in I$ is a demand node. The three different roles of nodes are mutually exclusive $P \cap M \equiv P \cap I \equiv I \cap M \equiv \emptyset$. The set of arcs $A \subseteq N \times N$ consists of arcs $a_{(i,j)}$ where (i, j) is a tuple of nodes $i, j \in N$. Model parameters and variables are depicted in table 5.3 and table 5.4, respectively.

The mine production cost $C_{m,t}$ is a potentially non-linear function of production volume $S_{m,t}$ and is modelled according to Golombek et al. (1995). In their paper, the authors present a production cost function for which the marginal supply cost curve has an intercept $\alpha_{m,t} \geq 0$ that then follows a roughly linear trend with slope $\beta_{m,t} \geq 0$ until production reaches almost capacity limit. As the supply level approaches production capacity limits, the marginal costs increase exponentially depending on the parameter $\gamma_{m,t} \leq 0$. The economic intuition for using this functional form of marginal costs is that prices during periods with higher demand are in reality often set by older operations. Coal mining conditions decline over time as cumulated coal production increases and the low-cost reserves are exploited. Moreover, coal mines may increase their production within a certain range by increasing their labour and machinery inputs above planned levels or by mining a coal seam that only becomes profitable if market prices exceed certain levels.

[74]Empirical evidence for steam coal market integration is given in Li (2008) and Warell (2006). Haftendorn and Holz (2010) find no empirical evidence for market power of exporting countries in the international steam coal trade market for the years 2005 and 2006. However, it has so far not been investigated whether single countries that control large state-owned mine enterprises can exert market power through volumes or through taxes. In the global steam coal market, a large number of both state-run mining enterprises and privately owned companies compete with each other. According to Ritschel (2010), the largest 10 internationally operating mining companies together controlled only about one quarter of the global hard coal mining production in 2009. Given the availability of additional reserves and potential mining capacity, the possibility for enterprises to exercise market power on the global steam coal market seems quite low in the long-run. Theoretically, the spatial price equilibrium in such a market is fundamentally marginal cost based (Samuelson, 1952).

[75]Model results will only be analysed until 2030 to ensure stability of results.

Table 5.3: Model parameters

Parameter	**Dimension**	**Description**
$c^{I,M}_{m,t}$	M\$$_{2009}$/Mtpa	Investment costs in region m for mine capacity investments I_{mt} in period t
$c^{I,P}_{p,t}$	M\$$_{2009}$/Mtpa	Investment costs in region p for port capacity investments $I^P_{p,t}$ in period t
$C_{m,t}$	M\$$_{2009}$/Mt	Mine production cost function in region m in period t
$c^{S,M}_{m,t}$	M\$$_{2009}$/Mt	Marginal mine production cost function in region m in period t
$c^T_{a_{(i,j)},t}$	M\$$_{2009}$/Mt	Specific transport costs on arc $a_{(i,j)}$ in period t
$Cap^M_{m,t}$	Mtpa	Existing mine capacity in region m in period t
$Cap^{M,max}_{m,t}$	Mtpa	Maximum mine capacity investment potential in mine region m in period t
$Cap^P_{p,t}$	Mtpa	Port capacity in port p in period t
$c^P_{p,t}$	M\$$_{2009}$/Mt	Specific turnover costs at port p in period t
$Cap^T_{a_{(i,j)},t}$	Mtpa	Transport capacity between node i and node j in period t
$D_{i,t}$	Mt	Steam coal demand in import region i in period t
d_t	-	Discount factor for period t

Table 5.4: Model variables

Variable	**Dimension**	**Description**
$S_{m,t}$	Mt	Amount of supply in mining region m in period t
$I^M_{m,t}$	Mtpa	Mine capacity investment in mine region m in period t
$I^P_{p,t}$	Mtpa	Port capacity investment at export harbor p in period t
$T_{a_{(i,j)},t}$	Mt	Total transport volume on arc $a_{(i,j)}$ in period t
$\mu_{n,t}$	M\$$_{2009}$/Mt	Marginal costs of supply in node n in period t
$\lambda_{m,t}$	M\$$_{2009}$/Mt	Capacity scarcity rent in mining region m in period t
$\epsilon_{p,t}$	M\$$_{2009}$/Mt	Capacity scarcity rent for export terminal p in period t

The marginal supply cost function $c^{S,M}_{m,t}$ of C_{mt} is then defined as:

$$c_{m,t}(S_{m,t}) = \alpha_{m,t} + \beta_{m,t} S_{m,t} + \gamma_{m,t} \ln \left(\frac{Cap^M_{m,t} + \sum_{t'=2011}^{t} I^M_{m,t'} - S_{m,t}}{Cap^M_{m,t} + \sum_{t'=2011}^{t} I^M_{m,t'}} \right), \quad \alpha_{m,t}, \beta_{m,t} \geq 0,\ \gamma_{m,t} \leq 0, \tag{5.1}$$

for $S_{m,t} \in [0, Cap^M_{m,t} + \sum_{t'=2011}^{t} I^M_{m,t'})$.

5.4.2 Model Formulation

The spatial equilibrium in the global steam coal market is modelled by minimising the total discounted system costs under a set of restrictions. This formulation is the dual problem of the welfare maximisation problem in a spatial market. The resulting equilibrium corresponds to a perfectly competitive market outcome with marginal cost-based allocation at each model node $n \in N$ and cost-based trade flows and investments in the network. The objective function consists of terms for production, transportation, turnover, and investment costs that every producer and port operator minimises with respect to satisfaction of demand. Producers sell their coal at export terminals to exporters and traders who ship the coal via bulk carriers on a least-cost basis to the demand centres. Turnover costs at coal export terminals are interpreted as marginal costs. With the mentioned assumptions in mind, this corresponds to minimising the sum of all cost components:

$$\min_{x\in\Omega} O(x) = \sum_{t\in T} d_t \Bigg[\sum_{m\in M} \Big(C_{m,t}(S_{m,t}) + c^{I,M}_{m,t} I^{I,M}_{m,t} \Big) + \sum_{a_{(i,j)}\in A} c^{T}_{a_{(i,j)},t} T_{a_{(i,j)},t} + \sum_{p\in P} \left(c^{P}_{p,t} \sum_{i\in I} T_{a_{(p,i)},t} + c^{I,P}_{p,t} I^{I,P}_{p,t} \right) \Bigg], \tag{5.2}$$

with the decision vector $x = (S_{m,t}, T_{a_{(i,j)},t}, I^{M}_{m,t}, I^{P}_{p,t})$ and Ω being the set of all feasible solutions. The objective function is convex, as $c_{m,t}$ is a convex function for $\gamma \leq 0$ (which is always the case), and all other cost components are convex in their respecting variables. The set of all feasible solutions Ω is restricted by a set of model constraints:

For mining nodes, steam coal production has to equal shipments to the export terminals:

$$S_{m,t} - \sum_{p\in P} T_{a_{(m,p)},t} = 0 \qquad (\mu_{m,t}) \qquad \forall m, t. \tag{5.3}$$

For port nodes, all inflows of steam coal from the mining regions have to match outgoing volumes:

$$\sum_{m\in M} T_{a_{(m,p)},t} - \sum_{i\in I} T_{a_{(p,i)},t} = 0 \qquad (\mu_{p,t}) \qquad \forall p, t. \tag{5.4}$$

Steam coal shipped to the import regions has to match demand:

$$\sum_{p\in P} T_{a_{(p,i)},t} - D_{i,t} = 0 \qquad (\mu_{i,t}) \qquad \forall i, t. \tag{5.5}$$

Coal production is restricted by mining region capacity limits. However, endogenous mine investments are possible from 2011 onwards:

$$S_{m,t} - \sum_{t'=2011}^{t} I^M_{m,t'} - Cap^M_{m,t} \leq 0, \qquad (\lambda_{m,t}) \qquad \forall m,t. \tag{5.6}$$

The same holds for port capacities:

$$\sum_{i \in I} T_{a_{(p,i)},t} - \sum_{t'=2011}^{t} I^P_{p,t'} - Cap^P_{p,t} \leq 0, \qquad (\phi_{p,t}) \qquad \forall p,t. \tag{5.7}$$

Furthermore, mine capacity expansions are limited by geographical, geological, political, and economic parameters. While such potentials are hard to estimate, they are necessary in order to prevent the most cost efficient mine regions from expanding beyond all realistic bounds. Typical estimates can be derived from expert opinions and market analyses. Maximum investment potential is based on Ritschel (2009b) so that it is possible to restrict:

$$\sum_{t'=2011}^{t} I^M_{m,t'} - Cap^{M,max}_{m,t} \leq 0, \qquad (\epsilon_{m,t}) \qquad \forall m,t. \tag{5.8}$$

The objective function and the restrictions (5.3) to (5.8) form the optimisation problem WCM. WCM is a convex minimisation problem with a non-empty set of feasible solutions. Such a model can be solved by standard non-linear programming solvers available in the programming package GAMS[76].

5.5 Database

To fully specify the model equations, data on costs and capacities are required. The process of data acquisition is a challenging task in itself, as information on steam coal markets is available only from a multitude of heterogeneous sources. While there are some publications on steam coal markets available from institutions like the IEA (IEA, 2009) or the EIA (EIA, 2006, 2010a,b), comprehensive information is especially obtained from the reports of the IEA Clean Coal Center: e.g. Baruya (2007, 2009), Minchener (2004, 2007) and Crocker and Kowalchuk (2008). Furthermore, Ritschel (2010) and Schiffer and Ritschel (2007) publish annual reports on the developments in the hard coal markets. Further publications include analyses from employees working for international utilities, like Bayer et al. (2009), Rademacher (2008), and Kopal (2007). Industry

[76] Another option is to programme the model in GAMS in the mixed complementarity format by deriving its equilibrium conditions (for MCP programming with GAMS see also Rutherford (1994) or Ferris and Munson (1998)). The equilibrium conditions can provide insights of what variables marginal costs of supply are composed of. The necessary equilibrium conditions can be found in appendix D. Both approaches yield the same optimal solution.

yearbooks and governmental reports provide useful information as in the case of China (CIRI, 2007, CMR, 2010, NBS, 2008). National statistics bureaus and mineral ministries provide high quality information, for example, ABARE (2008) and ABS (2006). Not mentioned is a larger number of coal company annual reports as well as information based on expert interviews. Furthermore, the present analysis is based on several extensive research projects at the Institute of Energy Economics at the University of Cologne. Trüby (2009) calculates marginal cost functions and freight costs for the international trade market for steam coal. This analysis is based on these cost functions for the international trade market. A summary of the findings and the methodology for computing the cost curves can also be found in Trüby and Paulus (2010). Eichmüller (2010) derives mining and transportation cost estimates as well as mining capacities for domestic markets in China and the U.S., which are implemented in the model used in the presented paper.

To account for the varying steam coal qualities worldwide, the WCM converts mass units into energy flows. All model outputs are therefore given in standardised energy-mass units with one tonne equaling 25120,8 MJ (or 6000 kcal per kg). Information on average energy content is based on IEA (2009), Ritschel (2009a), and BGR (2008).

5.5.1 Topology

Table 5.5 gives an overview of all 65 model nodes. To account for their dominant role in the global steam coal market, domestic markets of China and the U.S. have been explicitly modelled. Both countries together constitute around 75% of the global steam coal market supply and demand. For all other mining regions, the export production capacity is modelled as a residual of total production capacity minus domestic consumption. Each export port can ship coal to each of the importing regions. The term *new mine regions* refers to mine-type nodes that represent still-untapped mining potential in the respective regions. Mining regions are connected by arcs which represent inland transport infrastructure to the respective export ports in their country.

Transportation routes exist down the value stream from mining regions to the export terminals and then to the demand centres. In total, 287 transport routes have been modelled.

5.5.2 Supply Costs

Costs for mining include coal extraction costs, costs for coal processing and washing, as well as transportation costs within the coal mines. However, public information on the cost breakdown is mostly (if at all) only available for mine mouth or free-on-board costs. The data on mine-mouth costs was obtained through coal companies' annual reports of, expert interviews, and literature sources. The available data of mine-mouth cash costs

Table 5.5: Model topology

Mine regions	**Export terminals**	**Demand regions**	**New mine regions**
Queensland UG	Queensland	North-western Europe	Australia invest
Queensland OC	New South Wales	Mediterranean Europe	South Africa invest
New South Wales OG	South Africa	Japan	Indonesia invest
New South Wales UC	Indonesia	South Korea	Russia invest
South Africa OC	Russia Baltic	Taiwan	Colombia invest
South Africa UG	Russia Pacific	India west coast	USA invest
Indonesia	Russia med	India east coast	Venezuela invest
Russia Donezk	Colombia	USA - North Atlantic	China - Xinjiang invest
Russia Kuzbass	China	USA - South Atlantic	PRC - Shaanxi/IMAR invest
Colombia	USA east coast	USA - SE central	
China - Shaanxi	Venezuela	USA - SW central	
China - Shanxi	Vietnam	USA - Central	
China - Shangdong		USA - NW central	
China - Henan		USA - Western	
China - IMAR		Other Asia	
China - other		Brazil	
USA - Northern Appalachia		Chile	
USA - Southern Appalachia		China - Beijing	
USA - Illinois basin		China - Shanghai	
USA - Northern PRB		China - Hong Kong	
USA - Southern PRB		China - West	
Venezuela		China - North	
Vietnam			

Table 5.6: Input factors by relative importance for coal mining production costs in 2005

in %	Diesel	Explosives	Tyres	Steel products	Electricity	Labour	Chemicals
Room/Pillar	5-8	0-2	0	24-35	10-18	28-39	8-13
Longwalling	5-10	0-2	0	24-35	10-18	28-45	4-8
Dragline	14-18	15-20	5-10	22-28	5-12	18-32	1-4
Truck/Shovel	18-26	17-22	8-12	19-26	0-3	18-35	1-4

Source: Trüby and Paulus (2010). See also Trüby (2009).

and mine capacity is fitted to the marginal cost function described in section 5.4 by ordinary least squares (an overview of marginal mining costs can be found in appendix D in table D.1). In this way it is possible to model the characteristics and the absolute level of the production costs for each mining region.

For the projection of marginal mining costs until 2030, future mining costs are calculated by escalating the input factor prices for mining in accordance with their relative importance in the production process. The relative importance of input factors is derived from a number of sources. Table 5.6 gives an overview of the relevance of different input factors on mine production costs in 2005. In underground mining mostly longwalling and room-and-pillar technologies are applied. Open-cast mining sees dragline and truck-and-shovel operations (or a mix). For a more detailed description of mining technologies refer to Hustrulid (1982) or Darmstadter (1999).

Many of the relevant input factor prices for mining, including those for explosives, chemicals, and diesel, are correlated with the oil price. This is obvious, as the main production input for explosives (in this case ANFOs: Ammonium Nitrate Fuel Oil), chemicals, and diesel used in coal mining is oil. Therefore, a high correlation of these

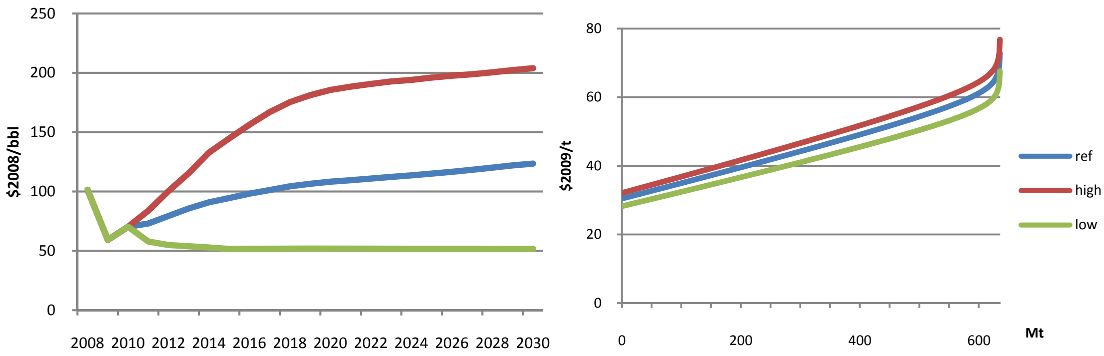

FIGURE 5.1: Influence of different oil price projections (left) on the marginal mining costs in Shanxi, China in 2030 (right)

TABLE 5.7: Demand figures for 2005 and 2006 and demand projections until 2030

Region	2005	2006	2020	2030
Europe	168	181	168	166
Japan	126	119	104	98
South Korea	63	60	95	111
Taiwan	61	58	69	81
India	22	25	72	107
Latin America	10	11	18	22
USA	990	978	914	968
People's Republic of China	1761	1932	3127	4190

Source: EIA (2010b).

input factor prices with the oil price for the future is also assumed. The analysis is based on the reference oil price projections published in EIA (2010b) as well as historical input factor price evolutions to estimate future factor prices. This methodology enables us to get consistent mining cost projections depending on different oil price projections. Figure 5.1 demonstrates how the oil price projections of the EIA for the 'high', 'reference', and 'low' oil price cases influence marginal coal production costs for Shanxi (PR of China) in the year 2030.

5.5.3 Demand

For the necessary demand projections up to 2030, hard coal demand growth projections of EIA (2010b) are used. The growth projections were taken from the *reference case*. Demand figures shown in table 5.7 are absolute demand figures for China and the U.S. For the other demand regions, these figures should be interpreted as import demand.

5.6 Scenario Design

In the scenario analysis, the feedback of two different Chinese bulk energy transport strategies on the coal supply mix in China and the repercussions on the global steam coal market are investigated. Bulk energy transport costs are an important determinant for the competitiveness of Chinese steam coal supply in the coastal demand centres where an opportunity for international coal imports exists. High domestic transport costs could lead to increased amounts of steam coal imports. This expansion of imports leads to higher global production and mines with higher costs becoming price setting. The slope of the global steam coal supply function determines how high the increase in marginal costs is.

Two scenarios are investigated: in the first scenario, it is assumed that current railway expansion plans continue and that regulatory and organisational hurdles for large-scale HVDC investments are not overcome. Additional coal transportation will then be handled by investment into railway capacity between the coal-bearing provinces and the coastal demand centres. In the second scenario, it is assumed that China rapidly overcomes the current barriers for HVDC investment by developing efficient incentive regimes for transmission operators and by empowering a national energy planning institution which is able to coordinate stakeholders and execute such a nationwide infrastructure project. Demand growth for coal transportation will therefore be covered by the installation of mine-mouth power plants in combination with HVDC transmission lines. Then the analysis shows how these bulk energy transport configurations affect the future Chinese steam coal supply and global steam coal market economics, focusing on marginal cost effects and on mining investments. Welfare effects accrued in China and worldwide between both scenarios, including the investment cost of the HVDC transmission lines, will also be considered. Both scenarios can be interpreted as bounds for a possible range of future market evolutions with regard to energy transport decisions in China.

5.6.1 Scenario 'coal-by-train'

In the first scenario, called 'coal-by-train', it is assumed that China will rely mainly on additional railway capacity to transport the additional coal output from the coal-bearing regions to the consumption areas. This will require massive amounts of investments into railway tracks, engines, rolling stock, and into the railway electricity grid. The investments into transport capacity will mainly take place from the central coal-bearing regions to Hong Kong, Shanghai, and Beijing (figure 5.2). While the mining capacity limits in the central Chinese regions can still be further extended, many of the mines are already operating deep underground at elevated costs. As Dorian (2005) and Taoa and Li (2007) state, future prospects could lie in the desert province of Xinjiang, where coal reserves are plentiful and could be mined in low-cost open-cast operations. Therefore, further investments will take place between the Western coal fields in Xinjiang and the central provinces. This scenario is in line with a number of railway expansion projects that have been issued by the Chinese government over the past decade to cope with the rising coal transport demand (Fedor, 2008, Sagawa and Koizumi, 2007). While railway transportation tariffs are high, these tariffs already include mark-ups for investment costs for railway expansion projects[77].

5.6.2 Scenario 'coal-by-wire'

In the second scenario, called 'coal-by-wire', it is assumed that, for new mining capacity in Shaanxi and the Autonomous Republic of Inner Mongolia (IMAR), China will build mine-mouth coal-fired power plants in combination with HVDC lines which transport the electricity to the demand centres in Beijing, Shanghai, and Hong Kong. Mine-mouth coal-fired power plants in combination with large-scale HVDC lines, which transport electricity to the coastal demand hubs, already exist to some degree and are increasingly the focus of Chinese grid planning authorities (Qingyun, 2005, Yinbiao, 2004). However, until now, long-range HVDC infrastructure from the West to the East has not been expanded on a very large scale in China for several reasons: so far, transmission and distribution tariffs are not necessarily determined competitively or cost-based so that the state-oriented grid companies have little direct incentive to increase infrastructure investment (Fedor, 2008, Minchener, 2007). China lacks the central energy planning institution necessary for the large-scale efficient realisation of HVDC grid infrastructure. Approval of large infrastructure investment projects is divided among many different departments. The weakness of central Chinese institutions regarding energy system planning and the fact that decisions are often made on the grass-roots level, has so far partly hindered the implementation of HVDC transmission lines (MIT, 2007).

The benefit of this approach is that the variable costs for transporting electricity via HVDC lines are practically zero. However, electricity losses apply, which are up to 3% depending on transmission distances (Bahrmann and Johnson, 2007). The Western province of Xinjiang is not suited for direct HVDC line connection as it is an arid, almost desert-like region. Therefore, it is unlikely that sufficient water for the cooling circuits of large-scale coal-fired generation capacity will be available there. It is assumed in this scenario that coal energy from Xinjiang will therefore be transported by a combination of transport modes; first coal will be moved via railway to the mine-mouth power plants in Shaanxi/IMAR. As a second step, the western coal will be combusted, and the generated electricity will be transported with HVDC lines to the demand centres along the coast.

As only the steam coal market is modelled, all numbers on coal trade flows in the coal-by-wire scenario from the new mining regions *Shaanxi/IMAR invest* and *Xinjiang*

[77] Transporting one tonne of coal by railway from Shanxi to Hong Kong cost about 36 $ in 2005 (CMR, 2010). The Chinese Ministry of Railways annually publishes their tariff quotas and the main components of these tariffs. They state one component for 'railway expansion projects' that reflects the costs necessary to cover full operating costs, including investments.

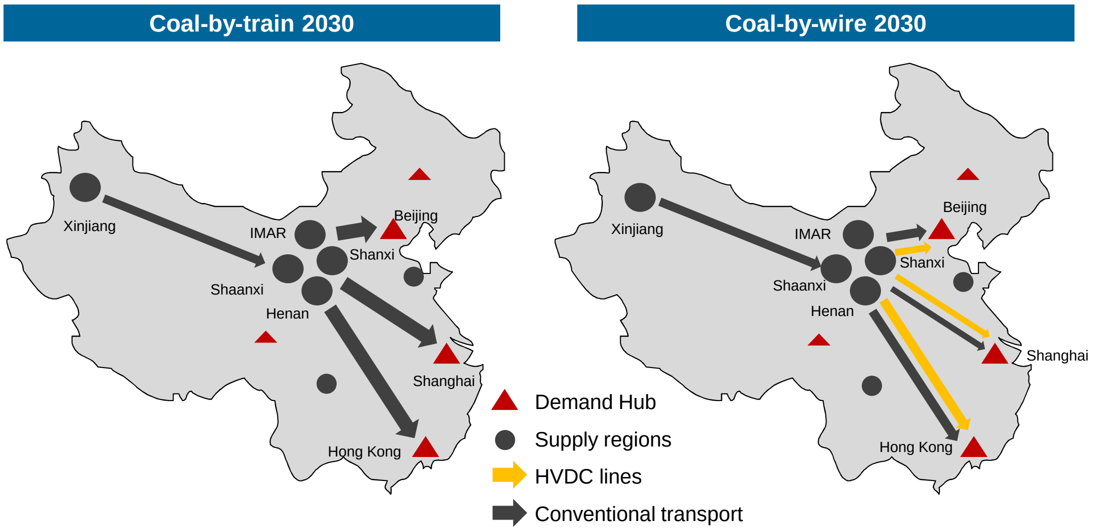

FIGURE 5.2: Topology of the scenario setup for China

TABLE 5.8: Domestic steam coal transport costs for new-built mines in both scenarios

		2005	2020		2030	
in $\$_{2009}$/t			coal-by-wire	coal-by-train	coal-by-wire	coal-by-train
costs from new mines in *Shaanxi/IMAR invest* to:						
	Hong Kong	36	0	59	0	69
	Shanghai	26	0	43	0	53
	Beijing	6	0	11	0	13
costs from *Xinjiang invest* to:[a]						
	Hong Kong	67	51	85	59	108
	Shanghai	59	51	74	59	95
	Beijing	54	51	69	59	87

[a]Note that in the 'coal-by-wire' scenario railway costs still apply for transporting coal volumes from Xinjiang to the mine-mouth coal fired power plants in Shaanxi/IMAR.

invest to the demand regions have to be understood as electricity equivalents. These coal trade flows are used in electricity generation at the mine-mouth power plants in Shaanxi/IMAR, and generated electricity is then transported via HVDC transmission to the coastal demand centres.

5.6.3 Scenario Parameters

Domestic transportation costs on the selected routes change between both scenarios as HVDC lines operate with zero variable transport costs. This does not reflect the full costs of the HVDC lines, as costs are allocated typically to electricity consumers. Later, welfare effects and the required HVDC investments will be compared. Secondly, transmission losses caused by the long-distance electricity transmission will be accounted for. Table 5.8 shows how transport costs differ between both scenarios.

The parameter settings for production costs, demand, port costs, and all other transport costs remain unchanged in both scenarios. Regarding the assumptions of future oil price evolution, the oil price projection of the *reference case* of EIA (2010b) is used in the analysis.

5.7 Results

In this section, the main model results for the two analysed scenarios, coal-by-train and coal-by-wire, will be outlined. The model is validated for the base years 2005 and 2006. Then the effects of the different Chinese bulk energy transport configurations on the future steam coal supply mix in China as well as on investments and welfare worldwide for 2020 and 2030 are analysed. A comprehensive overview of model trade flows and marginal costs for all model regions can be found in appendix D.

5.7.1 Coal Supply in China

The results for the years 2005 and 2006 show that the model is fairly accurately calibrated and can reproduce the historic transportation flows; the mean percentage error of all model trade flows in 2005 (and 2006) is 8.4% (8.6%). The root mean squared percentage error of all model trade flows in 2005 is 8.8% (8.5%).

Table 5.9 shows how Chinese coal demand is covered in both scenarios until the model year 2030. Model results for Chinese export volumes are less diversified than real export figures[78].

In the coal-by-train scenario, the main coal suppliers are the central Chinese provinces Shanxi, Shaanxi, and IMAR in 2030. A large proportion of the coal production is hauled via railway to the coastal demand centres. About 1155 Mt of Chinese production is transported to the Northern export terminals of Qinhuangdao and shipped via smaller bulk vessels or coastal barges to the Shanghai and Hong Kong demand regions. Western coalfields in Xinjiang province supply roughly 355 Mt of steam coal via overland transports in 2030. The production in the rest of China amounts to approximately 936 Mt and is therefore slightly above today's levels.

Imports play a significant role in the coal-by-train scenario, amounting to as much as 264 Mt. While this seems to be a fairly small volume compared to overall Chinese demand of more than 4 billion tonnes in 2030, it will make up 30% of the seaward traded

[78]In addition to statistical errors and differences in energy-mass conversions, coal quality is a factor which may cause model results to deviate to from real trade patterns. In Japan and South Korea, newer coal-fired power plants are highly efficient but very limited in the types of steam coal that they can use for generation. Coal specifications on sulphur, ash content, moisture, and volatile matter are important determinants, especially for newer coal-fired power plants. This dependence may sometimes lead to long-term bilateral contracts between single mines and plant operators as well as a certain price inelasticity of demand for certain coal types. Trade patterns caused by such coal quality requirements are not explicitly modelled and are beyond the scope of this analysis.

Table 5.9: Steam coal production, imports, and exports in China

	2005		2006		2020		2030	
in Mt	Reference[a]	Model	Reference[a]	Model	by-wire[b]	by-train	by-wire[b]	by-train
Shaanxi	154.4	143.8	184.9	149.5	132.2	171.1	177.0	177.0
Shanxi	426.7	417.6	454.9	478.3	540.8	605.6	650.5	662.9
Shandong	125.1	116.7	125.5	121.3	122.5	137.2	140.4	143.6
Henan	176.0	164.8	183.2	171.3	193.7	201.7	167.0	202.8
IMAR	165.3	198.1	192.1	207.7	185.0	210.7	228.4	246.1
China - Other	771.5	760.9	779.6	791.0	930.0	936.4	936.4	936.4
Shanxi/IMAR invest	0.0	0.0	0.0	0.0	659.9	639.1	1259.8	1220.1
Xinjiang invest	0.0	0.0	0.0	0.0	397.8	45.6	758.9	355.9
Imports:								
Indonesia	13.0	2.7	13.4	26.1	0.0	101.8	0.0	88.9
Australia	2.3	0.0	5.1	0.0	0.0	145.4	0.0	150.6
China (reimports)[c]	n/a	140.4	n/a	159.1	0.0	650.5	0.0	1155.4
Viet Nam	11.5	17.9	22.1	29.1	11.7	24.9	0.0	24.9
Exports:								
South Korea	18.5	62.9	17.2	44.2	16.2	95.3	68.5	22.9
Taiwan	20.9	0	14.6	0.0	0.0	0.0	0.0	0.0
China (reimports)[c]	n/a	140.4	n/a	159.1	0.0	650.5	0.0	1155.4
Japan	15.9	0	16.3	0.0	0.0	0.0	0.0	0.0

[a]The reference data for the years 2005 and 2006 stem from NBS (2009) and CIRI (2007) and may include some coking coal volumes.

[b]Energy equivalents for HVDC transmission losses are included in the figures for *Shaanxi/IMAR invest* and *Xinjiang invest* for the years 2020 and 2030.

[c]*China (reimports)* also includes Chinese coastal coal shipping by river barges or handysize bulk carrier vessels. Typically, the coal comes from the northern Chinese coal export terminals of Qinhuangdao and is shipped to the southern Chinese demand centres.

steam coal market. The main suppliers to China are Australian exporters with 151 Mt and Indonesian exporters with 89 Mt. Indonesian mines will experience significant cost increases until 2030 because of rising production costs. This is mainly caused by rising diesel prices as Indonesian mining operations are mostly open-cast truck-and-shovel operations and therefore are heavily exposed to oil price increases. Furthermore, Indonesian coal mining faces deteriorating geological conditions of coal deposits and qualities. Due to these elevated costs, Indonesia is the marginal supplier to China in the coal-by-train scenario and Indonesian mining costs plus transport charges constitute the marginal costs of supply to the Shanghai and Hong Kong regions.

In the coal-by-wire scenario, the situation is different. Investment in the Western province of Xinjiang is significantly higher. The construction of HVDC lines between central China's coal-bearing provinces and the coastal areas reduces transportation costs for the Western provinces and therefore incentivises investments. Therefore, the scenario results show a strong increase in mining capacity in the West as the mining costs in this region are fairly low, lying in the range of 11 to 22 $\$_{2009}$/t by 2030. With the reduced transport cost burden, these mines are among the cheapest suppliers in China in the scenario coal-by-wire in 2030. Re-imports do not play a role, as inland transportation of coal-based electricity is far more cost competitive than coastal shipping. Imports from foreign countries will be replaced completely by cheaper domestic production by 2030.

Table 5.10: Evolution of long-run marginal costs of supply for demand regions in Europe, China, and Japan

	2005		2006		2020		2030[b]	
in $\$_{2009}$/t (of coal)	Reference[a]	Model	Reference[a]	Model	by-wire	by-train	by-wire	by-train
Beijing	52	51	50	54	63	67	76	97
Shanghai	62	60	58	63	83	88	84	122
Hong Kong	62	60	58	63	83	93	84	126
PRC - West	n/a	53	n/a	56	72	81	108	112
PRC - North	n/a	40	n/a	44	81	85	97	118
Japan	63	60	63	63	83	90	97	121
Northwestern Europe	69	67	69	67	97	102	110	120
Mediterranean Europe	73	66	69	67	88	93	102	121

[a]The reference data for the years 2005 and 2006 stem from IEA (2009) and from EIA (2006). The IEA only publishes an average import price for each country. The reference country for the model region 'Northwestern Europe' are the Netherlands, while the reference country for 'Mediterranean Europe' is Italy. The EIA only publishes consumer prices for coal in general not distinguishing between anthracite, lignite, and bituminous coal. The reference price for China in 2005 and 2006 is estimated on the basis of coal reports from McCloskey. Note that deviations may arise as model results are standardised energy-mass units (25,120 MJ per tonne) while IEA data is in metric tonnes.

In this scenario, China is even able to export 69 Mt.

5.7.2 Long-run Marginal Costs of Steam Coal Supply

With the different allocation of volumes between both scenarios, the marginal costs of supply also change[79]. As cheaper volumes become available, high-cost suppliers are pushed out of the market and the marginal costs of supply to import regions decline.

Table 5.10 depicts the evolution of long-run marginal costs (LRMC) of supply for both scenarios until 2030. Two observations can be made: firstly, the LRMC are growing more similar over time in China, Europe, and Japan in both scenarios. Secondly, the LRMC are different in the two scenarios, with the coal-by-train scenario generally having higher marginal costs.

The two main drivers for the cost increase over time are the input price evolution of mine costs and the growing global demand for steam coal. The increase in input prices is mainly linked to the assumptions made on the oil price evolution, which affects coal mining costs. The increase in demand leads to increasing investment in mine capacity and a higher utilisation of existing mines. Both drivers have a cost-raising effect, as investments have to be refinanced and the higher utilisation rates of mines or utilisation of thus far extra-marginal mines, raises marginal production costs.

The lower LRMC in Europe, Japan, and especially China in the scenario coal-by-wire in 2030 are caused by the additional Chinese mining capacity which is developed in the Western province of Xinjiang. This mining capacity becomes highly cost competitive

[79]Marginal costs deducted from the model can be interpreted as the cost for supplying an additional unit of coal to a specific geographical region. They therefore cover all costs in the model: mine production costs, transport costs, turnover costs. The projected marginal costs for 2020 and 2030 also cover mine and port capacity investments.

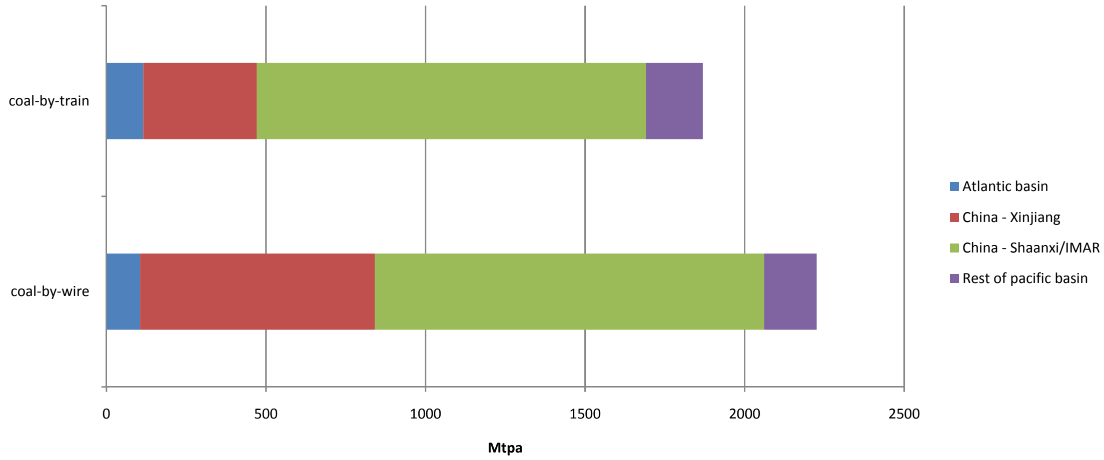

FIGURE 5.3: Cumulated mining investments in millions of tonnes per year in the global steam coal market until 2030

through the installation of HVDC lines within China that reduce transport costs of steam coal. However, the gap in LRMC between both scenarios is different for China and for Europe; the marginal cost supplier for Europe in this scenario changes from the U.S. to Russia. Russian mines are operating in a very broad cost range between 27 and 91 $\$_{2009}$/t in 2030. However, long railway haulage distances to the export terminals in the Black Sea, the Baltic Sea, or the Pacific significantly increase costs of supply. Therefore, the difference in marginal costs of supply to Europe of Appalachian mines and the Russian mines is not too large. The difference in European LRMC between both scenarios of approximately 10% to 20% can be basically interpreted as the difference of marginal costs of supply to Europe between the U.S. Appalachian mines and Russian mines in 2030.

The situation for China, however, is different. Here, the marginal supplier changes from high-cost foreign mines to lower-cost domestic Chinese mines. The difference in LRMC of supply between those foreign imports and Chinese mines is significant and in the range of 37 $\$_{2009}$/t to 42 $\$_{2009}$/t in 2030.

5.7.3 Investments and Utilisation of Mining Capacity

Figure 5.3 shows the cumulated mining investments for both scenarios until 2030. Global mining capacity additions in the coal-by-train scenario amounts to 1927 Mtpa and in the coal-by-wire scenario up to 2254 Mtpa. The difference in mining investments between both scenarios is largely explained by the higher investments in Xinjiang. Investments into mining capacity in Western China are by about 380 Mt higher in the coal-by-wire scenario. Mining investments in the rest of the world are approximately 50 Mtpa lower in the coal-by-wire scenario. Fewer investments mainly take place in the U.S., Russia, and Indonesia.

Table 5.11: Utilisation rates of U.S. and Chinese mines

	2020		2030	
in [%]	coal-by-wire	coal-by-train	coal-by-wire	coal-by-train
USA - Northern Appalachia	57	62	69	84
USA - Southern Appalachia	64	69	75	89
USA - Illinois basin	100	100	100	100
USA - Northern PRB	97	97	98	99
USA - Southern PRB	39	39	64	86
Shaanxi	75	97	100	100
Shanxi	82	91	98	100
Shandong	85	96	98	100
Henan	96	99	82	100
IMAR	75	86	93	100

The difference in mining investments leads to a change in mine utilisation rates. On a global scale, supply and demand intersect in the flat part of the global supply cost curve in the coal-by-wire scenario due to the availability of additional mining capacity. Existing high-cost mines have a lower output since the new, cheaper Chinese capacity coming on-line partly crowds them out. Table 5.11 shows mine utilisation levels for Chinese and US mining regions for both scenarios. The main differences in mine utilisation can be found in the Appalachian regions, the Southern Powder River Basin, and the Chinese provinces of Shanxi, Shaanxi, and Shandong. Supply-wise, the Appalachian mines are amongst the most expensive capacities in existence. In China, the high-costs mines in Shanxi, Shandong, and IMAR provinces experience a decrease of utilisation levels in 2020. Shanxi coal deposits have already been mined for a long time with most operations being deep underground at elevated costs. Therefore, the cheaper western mines reduce the output of existing Chinese mines by 160 Mt in 2020 and another 70 Mt in 2030.

5.7.4 Welfare Effects

Overall lower marginal costs in the coal-by-wire scenario lead to welfare effects and changes in the spatial distribution of rents[80] (figure 5.4). In total, gross welfare effects are positive and amount to 248 billion $\$_{2009}$ in 2030. However, while consumers, especially in China, benefit with regard to allocation of welfare changes, producer rents are shrinking worldwide. As the intersection of global demand and supply moves to the flat part of the global supply cost curve, producer rents decrease. In the coal-by-wire scenario, producer rents in countries other than China are dropping by 163 billion $\$_{2009}$. This is mainly caused by lower global marginal cost levels as well as lower utilisation of high-cost U.S. mines, which cut into producer surpluses. Producer rents for China also slightly

[80]Spillover welfare effects for downstream electricity markets are not accounted for.

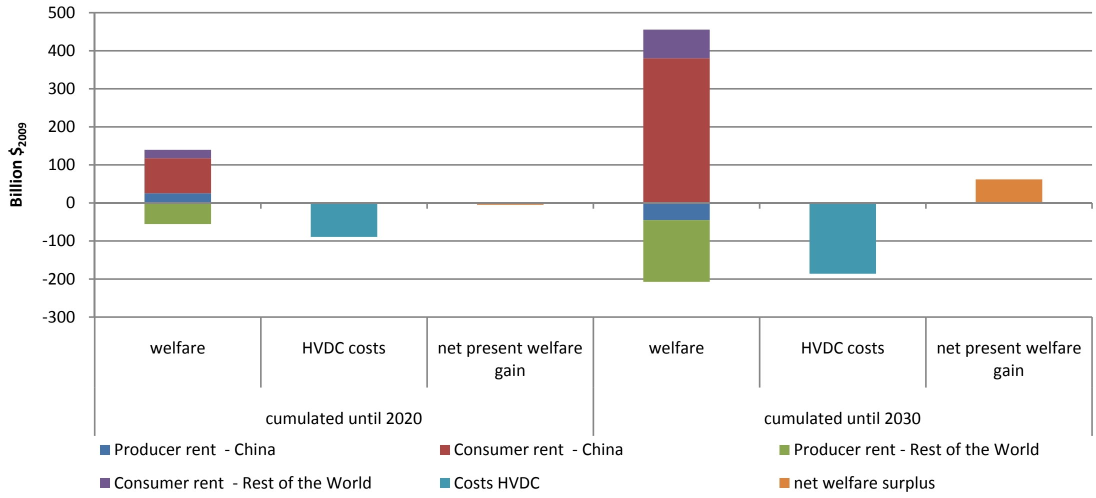

FIGURE 5.4: Cumulated net present welfare and cost effects between both scenarios until 2020 and until 2030 (horizontal axis represents the coal-by-train scenario).

decrease in the scenario coal-by-wire. If argued from the point of view of the coal-by-train scenario, producers outside China benefit from high prices and the Chinese need for imports.

Consumers benefit on a global scale in the coal-by-wire scenario. The difference in consumer rent makes up 456 billion $\$_{2009}$ cumulated until 2030. The biggest portion of this increase is allocated to China, as the difference in marginal costs of supply between both scenarios is the largest there.

To analyse welfare effects of HVDC investments, the net present value of welfare gains or losses and investment costs is computed[81]. The additional HVDC grid which interconnects the mine-mouth coal-fired power plants at new mines in Shaanxi and IMAR with the coastal demand regions of Beijing, Shanghai, and Hong Kong amount to 186 billion $\$_{2009}$ until 2030. While these investment figures seem to be high, one must keep in mind the assumption that China is facing an increase of steam coal demand of 2 billion tonnes by 2030. The assumed increase in Chinese coal demand is equal to roughly 40% of the current global steam coal consumption.

On a global scale, the 'coal-by-wire' configuration leads to cumulated net present welfare gains of -5 billion $\$_{2009}$ by 2020 and 62 billion $\$_{2009}$ by 2030. This may seem quite modest compared to the investment costs and welfare changes involved. However,

[81]HVDC investment cost data, as well as loss ratios for HVDC configurations, are based on Bahrmann and Johnson (2007). They investigate different configurations for power transmission between coal production sites in Utah and California. A +2x 500 kV double bipole DC configuration with maximum transmission losses of up to 3.35% at full load depending on transmission distance is assumed. HVDC investments are annuised over a period of 30 years. All welfare effects are present values discounted with a 7% interest rate. Discount rates aligned to values for less-developed countries with high growth rates found in Evans and Sezer (2005). It is also assumed that new coal-fired power plants in China run 6,800 full load hours per year on average and have efficiency levels of 43%. Avoided investments into railway capacity are not accounted for, as the transport rates used in the model runs already reflect full costs of operation, including railway construction costs.

if the welfare analysis just focuses on China, the picture changes; cumulated net welfare surplus including HVDC investments for China amounts to 28 billion $\$_{2009}$ by 2020 and 149 billion $\$_{2009}$ by 2030. Producers in the rest of the world would be worse off in the coal-by-wire scenario. Production of high-cost mining companies in the U.S. could be crowded out, and cost-competitive suppliers in Australia, South Africa and domestic U.S. suppliers could face severely reduced profits as a result of the price pressure induced by new mines in Xinjiang, Shaanxi, and IMAR.

5.8 Conclusions

The presented paper analyses the influence of Chinese bulk energy infrastructure investment decisions on the steam coal supply mix in China and on investment and welfare spillover effects in the world market. A spatial equilibrium model which includes domestic markets for China and the U.S. as well as the main importers and exporters is presented. Proxies for future marginal costs of supply are based on a rigid cost structure decomposition which allows us to deduct future supply cost estimates based on assumptions of input price evolutions. The presented paper then analyses two scenarios with different assumptions of future Chinese energy transport investment policy; in one scenario it is assumed that current railway expansion will continue in the future as rapid realisation of HVDC transmission lines is hindered by existing organisational and regulatory barriers. In the other scenario, it is assumed that hurdles for HVDC investments in China are reduced. Thus, rapid implementation of transmission lines in combination with new coal-fired power stations close to the mines can take place on a very large scale.

According to the results, such infrastructure decisions yield a significant change in LRMC for China by up to 33% in 2030. China is able to feed its domestic steam coal demand through domestic production in the scenario with HVDC build-up. Therefore, it crowds out foreign steam coal volumes mainly originating from Australia and Indonesia. In the case of coal transport by railway, China will have to import significant quantities that make up about 30% of the steam coal trade market volume in 2030. LRMC for steam coal in Europe and Japan change only moderately between both scenarios. The reason for this is that one high-cost supplier (USA) is exchanged for another (Russia).

The analysis shows that large-scale investments into HVDC transmission until 2030 yield mostly positive economic effects, especially for China. This result should encourage Chinese policy makers to rapidly overcome the hindrances this large-scale infrastructure project currently faces; China's national institutions engaged in energy are fragmented and do not coordinate well. Aspects like setting electricity and fuel prices as well as the approval of large infrastructure investments are divided among many different departments. To give such a large-scale national infrastructure project a good chance of rapid realisation, the national government would have to cut into this well-established web of local decision makers and form a central energy planning institution which has enough executive power.

As steam coal consumers benefit on a global scale from the Chinese HVDC transmission lines, results should encourage large utilities or energy-intensive industries to support Chinese grid investment efforts. Support could mean either helping to finance such projects or to provide, if needed, technological expertise in the field of high-voltage or even ultra-high-voltage transmission.

International mining companies will face increasing price pressure from the higher competitiveness of Chinese steam coal supply in the case of HVDC investments. This implies the need for mining companies to strengthen their exploration efforts in order to generate reserves which are mineable at low costs.

It is suggested that further research investigates in more detail how the steam coal supply mix of the other key world market actors like Europe, Japan, and the U.S. is influenced by Chinese infrastructure decisions. In this context, it would be especially interesting to see how such feedback affects power plant investment decisions in the important import regions in the long-run. Another research venue could be to investigate how potential future market players like Mozambique, Botswana, or Madagascar influence these results, especially regarding spatial distribution of mining investment decisions.

Appendix A

Supplementary Data for Chapter 2

Computational details

The model described in section 2.3.3 is implemented in GAMS and solved as a non-linear programme using the convert tool NLPEC for MPECs (Ferris et al., 2002, see also GAMS, nd). In essence, this tool automatically reformulates MPECs as standard non-linear programmes, hence enabling solution using existing non-linear programming algorithms. The convert tool provides various reformulation options of an original MPEC.

The original MPEC in this paper has 5,140 variables, 69,169 nonzero elements, and 4,240 single equations. I test several reformulation methods as described in Ferris et al. (2002) and GAMS (nd) with the MPEC described in this paper, and identify candidates that produce satisfactory solutions.[82] Although there are several more, a set of five key options essentially defines the reformulation method applied.[83] These are 1) *RefType* which defines the reformulation type, 2) *slack* which determines what type of slacks to put in, 3) *constraint* which determines if certain constraints are written down using equalities or inequalities, 4) *aggregate* which determines if certain constraints are aggregated or not, 5) *NCP bounds* which puts explicit bounds on arguments of NCP functions.

Table A.1 gives an overview of selected reformulation settings as tested in this paper. The reformulation methods 1 to 3 are invoked by the option *mult* and are based on product reformulation. These three reformulations deliver equal locally optimal solutions.[84]

[82] Criteria for identifying satisfactory and consistent solutions were: price convergence in import regions (as well as generally positive prices), positive output of at least one follower and positive output of the leader, lower prices in the Stackelberg model compared to the Cournot cartel model, higher profits for the leader compared to being a player in the Cournot cartel scenario, lower profits for the followers in the Stackelberg model as compared to the Cournot cartel solution.

[83] The description of the reformulation methods in this section closely follows GAMS (nd).

[84] The model is implemented as a minimisation problem in GAMS and consequently the optimal objective value is negative.

Table A.1: Selected reformulation methods as applied to the original MPEC

Reformulation	RefType	slack	constraint	aggregate	NCP bounds	Other options	Solution	objective value
1	mult	none	inequality	none	none		locally optimal	-45152.14757
2	mult	none	equality	none	none		locally optimal	-45152.14757
3	mult	positive/one	equality/inequality	none	none		locally optimal	-45152.14757
4	min	positive	equality	none	function		intermediate infeasible	4111.272474
5	fFB	free	equality	none	none	initmu 1e-2	locally infeasible	-33595.09814
6	fBill	positive	equality	none	none		intermediate infeasible	23930.2628
7	Bill	positive	equality	none	none		intermediate infeasible	10580.54758
8	CMxf	positive	equality	none	function		intermediate infeasible	27392.4249
9	penalty	positive	equality	none	none		intermediate nonoptimal	-45354.28784
10	penalty/mult	none/positive	equality	partial/none	none	initmu 1.0 numsolves 2 updatefac 0.1 0.2	locally optimal	-45152.14758

The solutions are economically consistent and not refuted by the test model for optimal follower behaviour (see below). CONOPT solves these reformulated models in about 38 seconds.

Reformulations 4 to 8 are based on NCP functions. The used settings are: *min* (minimisation of the NCP function), *fFB* (Fischer Burmeister NCP function), *fBill* and *Bill* (Billups function for doubly-bounded variables), *CMxf* (Chen-Mangasarian NCP function). This class of reformulation methods does not deliver satisfactory results.

Reformulation approaches 9 and 10 use the *penalty* option which penalises non-complementarity in the objective function. The latter of the two reformulations delivers a locally optimal solution that deviates from solutions 1 to 3 only in the fifth decimal point. Yet, the computation time is significantly longer, about three minutes .

Test model for optimal follower behaviour

To test for ex-post optimal follower behaviour in the Stackelberg model, objective function (2.3) and inequalities (2.4) and (2.5) are reformulated with $Z_j^{MPEC} = X_{-i,j}^{MPEC} + Q_j^{MPEC}$ being the optimal quantities of the other market participants from the solution of the original MPEC (as oulined in section 2.3.3), and $X_{i,j}^{test} = \sum_{m \in M_i} x_{m,j}^{test}$ being the output decision of the test problem.

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(Z_j^{MPEC} + X_{i,j}^{test} \right) \cdot X_{i,j}^{test} - \tau_{m,j} \cdot x_{m,j}^{test} - c_{m,j} \cdot x_{m,j}^{test} \right] \tag{2.3a}$$

Subject to:

$$Cap_m \geq \sum_{j \in J} x_{m,j}^{test} \tag{2.4a}$$

$$x_{m,j}^{test} \geq 0 \tag{2.5a}$$

Quasi-concave equation (2.3a) and linear inequalities (2.4a) and (2.4a) form a non-linear (konvex) optimisation problem with a unique solution which is solved in GAMS using CONOPT. The follower's profits in the test problem being equal to the follower's profits from the Stackelberg model $\Pi_i^{test} = \Pi_i^{MPEC}$ is a necessary (though not sufficient) condition for the solution of the in section 2.3.3 outlined MPEC being optimal. The results described in this paper satisfy this condition and generally also $X_{i,j}^{test} = X_{i,j}^{MPEC}$ but not necessarily $x_{m,j}^{test} = x_{m,j}^{MPEC}$.

Trade-flows data

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	27.0	7.0	4.1	24.4	0.7
Japan	50.2	8.6	2.0	1.3	1.6
Korea	8.4	5.1	0.4	1.0	1.2
Chinese Taipei	6.4	1.1	0.0	0.1	0.0
China	1.5	0.5	0.2	0.0	0.6
India	24.2	0.0	0.0	1.4	0.8
Brazil	3.9	1.4	0.0	5.5	0.5
Other					
Latin America	1.9	1.2	0.0	1.1	0.0
Other	13.4	0.2	0.8	0.6	3.0

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	15.7	3.5	3.7	18.4	1.3
Japan	42.1	6.7	1.3	0.6	0.2
Korea	12.8	4.4	0.5	1.6	1.0
Chinese Taipei	2.6	0.8	0.1	0.1	0.0
China	14.8	3.7	1.1	0.9	1.8
India	24.0	0.0	0.0	1.9	0.3
Brazil	4.1	0.9	0.0	6.7	0.0
Other					
Latin America	1.7	0.4	0.0	1.0	0.0
Other	7.5	0.2	0.0	0.5	2.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	20.7	4.8	4.3	27.7	0.8
Japan	45.8	8.7	2.1	2.7	0.4
Korea	17.4	5.3	1.3	2.7	0.7
Chinese Taipei	7.4	0.6	0.1	0.2	0.0
China	21.9	4.3	2.5	3.8	1.1
India	32.3	0.0	0.0	2.3	0.1
Brazil	4.2	1.6	0.1	7.1	0.0
Other					
Latin America	1.5	0.5	0.0	1.0	0.8
Other	3.5	0.2	0.1	0.2	2.5

TABLE A.2: Real market trade-flows in million tonnes

Source: Derived from IEA (2011a),IEA (2010a),IEA (2009).

eta = -0.1

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	39.6	7.8	5.0	8.1	3.1
Japan	41.0	7.9	4.9	7.7	2.9
Korea	10.2	2.0	1.2	1.9	0.8
Chinese Taipei	4.9	0.9	0.6	0.9	0.4
China	1.8	0.4	0.2	0.3	0.1
India	17.0	3.2	1.9	3.2	1.3
Brazil	7.2	1.4	0.8	1.4	0.6
Other Latin America	2.7	0.5	0.3	0.5	0.2
Other	2.4	0.5	0.3	0.5	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	26.3	4.7	2.0	5.2	2.2
Japan	32.3	5.7	2.4	6.0	2.1
Korea	12.8	2.2	0.9	2.4	0.9
Chinese Taipei	2.3	0.4	0.2	0.4	0.2
China	14.1	2.4	1.0	2.6	1.0
India	16.6	2.9	1.1	3.1	1.2
Brazil	7.4	1.3	0.5	1.4	0.6
Other Latin America	1.9	0.3	0.1	0.4	0.2
Other	1.2	0.2	0.1	0.2	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	34.8	6.8	3.6	7.4	2.4
Japan	36.1	7.0	3.6	7.5	2.3
Korea	16.5	3.2	1.7	3.4	1.1
Chinese Taipei	5.1	1.0	0.5	1.0	0.3
China	20.4	3.9	2.0	4.2	1.3
India	20.9	4.0	2.1	4.4	1.4
Brazil	7.9	1.5	0.8	1.7	0.5
Other Latin America	2.3	0.4	0.2	0.5	0.2
Other	1.0	0.2	0.1	0.2	0.1

eta = -0.2

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	40.0	8.2	4.7	9.9	3.0
Japan	42.2	8.3	4.3	9.0	3.0
Korea	10.5	2.1	1.1	2.2	0.8
Chinese Taipei	5.1	1.0	0.5	1.1	0.4
China	1.9	0.4	0.2	0.4	0.1
India	17.5	3.3	1.6	3.8	1.4
Brazil	7.4	1.4	0.7	1.7	0.5
Other Latin America	2.7	0.5	0.3	0.6	0.2
Other	2.4	0.5	0.2	0.6	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	27.1	4.5	2.1	5.5	2.1
Japan	33.8	5.4	2.4	6.1	1.9
Korea	13.4	2.1	1.0	2.4	0.8
Chinese Taipei	2.4	0.4	0.2	0.4	0.1
China	14.7	2.3	1.0	2.6	0.9
India	17.3	2.7	1.1	3.2	1.2
Brazil	7.6	1.2	0.5	1.5	0.6
Other Latin America	2.0	0.3	0.1	0.4	0.1
Other	1.3	0.2	0.1	0.2	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	35.8	6.8	2.4	8.6	2.4
Japan	37.4	7.0	2.4	8.5	2.2
Korea	17.1	3.2	1.1	3.9	1.1
Chinese Taipei	5.3	1.0	0.3	1.2	0.3
China	21.2	3.9	1.3	4.8	1.3
India	21.7	4.0	1.3	5.0	1.4
Brazil	8.1	1.5	0.5	1.9	0.6
Other Latin America	2.4	0.4	0.1	0.6	0.2
Other	1.1	0.2	0.1	0.2	0.1

eta = -0.3

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	41.3	8.2	4.2	11.0	2.8
Japan	44.2	8.3	3.7	9.5	3.1
Korea	11.0	2.0	0.9	2.4	0.9
Chinese Taipei	5.3	1.0	0.4	1.1	0.4
China	2.0	0.4	0.2	0.4	0.1
India	18.4	3.3	1.3	4.1	1.4
Brazil	7.7	1.5	0.5	1.9	0.5
Other Latin America	2.9	0.5	0.2	0.7	0.2
Other	2.5	0.5	0.2	0.6	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	25.9	5.0	2.2	6.2	2.1
Japan	32.8	6.0	2.4	6.7	1.9
Korea	12.9	2.4	1.0	2.6	0.9
Chinese Taipei	2.4	0.4	0.2	0.5	0.2
China	14.3	2.5	1.0	2.9	0.9
India	16.8	3.0	1.0	3.5	1.2
Brazil	7.4	1.4	0.4	1.7	0.6
Other Latin America	2.0	0.4	0.1	0.4	0.1
Other	1.2	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	35.0	6.8	2.5	9.6	2.4
Japan	37.0	7.0	2.4	9.3	2.1
Korea	16.9	3.2	1.1	4.2	1.1
Chinese Taipei	5.2	1.0	0.3	1.3	0.3
China	20.9	3.9	1.3	5.2	1.3
India	21.5	4.0	1.2	5.5	1.4
Brazil	8.0	1.5	0.4	2.1	0.6
Other Latin America	2.3	0.4	0.1	0.6	0.2
Other	1.0	0.2	0.1	0.3	0.1

TABLE A.3: Stackelberg model: Trade-flows in million tonnes for $eta = -0.1$ to $eta = -0.3$

Source: own analysis.

eta = -0.4

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	41.0	8.3	4.4	12.5	2.6
Japan	44.6	8.3	3.7	10.4	3.2
Korea	11.1	2.0	0.9	2.6	0.9
Chinese Taipei	5.4	1.0	0.4	1.2	0.4
China	2.0	0.4	0.1	0.5	0.2
India	18.6	3.2	1.2	4.5	1.5
Brazil	7.7	1.5	0.5	2.1	0.5
Other Latin America	2.9	0.5	0.2	0.8	0.2
Other	2.5	0.5	0.2	0.7	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	27.0	4.7	2.3	6.4	1.9
Japan	34.5	5.6	2.4	6.5	1.9
Korea	13.6	2.2	1.0	2.6	0.9
Chinese Taipei	2.5	0.4	0.2	0.5	0.2
China	15.1	2.4	1.0	2.8	0.9
India	17.7	2.8	1.0	3.5	1.2
Brazil	7.7	1.3	0.4	1.7	0.6
Other Latin America	2.0	0.3	0.1	0.4	0.1
Other	1.3	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	36.3	6.8	2.5	10.0	2.5
Japan	38.6	7.0	2.4	9.5	2.1
Korea	17.6	3.2	1.1	4.4	1.1
Chinese Taipei	5.4	1.0	0.3	1.3	0.3
China	21.9	3.9	1.3	5.3	1.3
India	22.4	4.0	1.2	5.6	1.5
Brazil	8.3	1.5	0.4	2.2	0.6
Other Latin America	2.4	0.4	0.1	0.6	0.2
Other	1.1	0.2	0.1	0.3	0.1

eta = -0.5

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	40.9	8.3	4.6	13.8	2.4
Japan	45.2	8.3	3.6	11.2	3.3
Korea	11.2	2.0	0.9	2.8	1.0
Chinese Taipei	5.4	1.0	0.4	1.3	0.4
China	2.0	0.4	0.1	0.5	0.2
India	18.9	3.2	1.1	4.9	1.5
Brazil	7.8	1.5	0.4	2.4	0.5
Other Latin America	2.9	0.5	0.2	0.9	0.2
Other	2.5	0.5	0.2	0.8	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	28.4	4.3	2.4	6.4	1.8
Japan	36.4	5.1	2.5	6.3	2.0
Korea	14.3	2.0	1.0	2.5	0.9
Chinese Taipei	2.6	0.4	0.2	0.4	0.2
China	16.0	2.1	0.9	2.7	1.0
India	18.7	2.5	0.9	3.4	1.2
Brazil	8.2	1.2	0.4	1.7	0.6
Other Latin America	2.2	0.3	0.1	0.4	0.1
Other	1.3	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	36.0	6.8	2.6	11.1	2.4
Japan	38.7	7.0	2.4	10.5	2.1
Korea	17.6	3.2	1.1	4.8	1.1
Chinese Taipei	5.5	1.0	0.3	1.5	0.3
China	22.0	3.9	1.2	5.9	1.3
India	22.5	4.0	1.1	6.2	1.5
Brazil	8.3	1.5	0.4	2.4	0.6
Other Latin America	2.4	0.4	0.1	0.7	0.2
Other	1.1	0.2	0.1	0.3	0.1

eta = -0.6

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	40.5	8.4	4.8	15.7	2.2
Japan	45.4	8.3	3.6	12.5	3.4
Korea	11.2	2.0	0.9	3.1	1.0
Chinese Taipei	5.5	0.9	0.4	1.5	0.5
China	2.0	0.3	0.1	0.5	0.2
India	19.0	3.1	1.0	5.5	1.5
Brazil	7.8	1.5	0.4	2.7	0.5
Other Latin America	2.9	0.6	0.2	1.0	0.2
Other	2.5	0.5	0.2	0.9	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	27.9	4.6	2.4	6.8	1.8
Japan	36.2	5.5	2.5	6.5	1.9
Korea	14.2	2.2	1.0	2.6	1.0
Chinese Taipei	2.6	0.4	0.2	0.5	0.2
China	15.9	2.3	0.9	2.8	1.0
India	18.7	2.7	0.9	3.6	1.2
Brazil	8.1	1.3	0.4	1.8	0.6
Other Latin America	2.1	0.3	0.1	0.5	0.1
Other	1.3	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	35.8	6.9	2.7	12.3	2.4
Japan	38.8	7.0	2.4	11.5	2.1
Korea	17.6	3.2	1.1	5.3	1.1
Chinese Taipei	5.5	1.0	0.3	1.6	0.3
China	22.0	3.9	1.2	6.4	1.3
India	22.6	3.9	1.1	6.8	1.4
Brazil	8.3	1.5	0.4	2.7	0.6
Other Latin America	2.4	0.4	0.1	0.8	0.2
Other	1.1	0.2	0.1	0.4	0.1

TABLE A.4: Stackelberg model: Trade-flows in million tonnes for $eta = -0.4$ to $eta = -0.6$

Source: own analysis.

eta = -0.7

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	40.0	8.4	4.9	17.5	2.0
Japan	45.7	8.3	3.5	13.8	3.5
Korea	11.3	2.0	0.9	3.4	1.1
Chinese Taipei	5.5	0.9	0.4	1.6	0.5
China	2.1	0.3	0.1	0.6	0.2
India	19.2	3.1	0.9	6.1	1.6
Brazil	7.8	1.5	0.4	3.0	0.5
Other					
Latin America	2.9	0.6	0.1	1.1	0.2
Other	2.5	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	28.2	4.6	2.5	7.2	1.7
Japan	37.0	5.5	2.5	6.7	1.9
Korea	14.5	2.1	1.0	2.6	1.0
Chinese Taipei	2.7	0.4	0.2	0.5	0.2
China	16.3	2.3	0.9	2.8	1.0
India	19.1	2.6	0.8	3.7	1.2
Brazil	8.2	1.2	0.3	1.9	0.6
Other					
Latin America	2.2	0.3	0.1	0.5	0.2
Other	1.3	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	35.7	6.9	2.7	13.4	2.4
Japan	38.8	7.0	2.5	12.5	2.0
Korea	17.7	3.2	1.1	5.7	1.1
Chinese Taipei	5.5	1.0	0.3	1.7	0.3
China	22.0	3.9	1.2	7.0	1.3
India	22.6	3.9	1.0	7.4	1.4
Brazil	8.2	1.5	0.4	2.9	0.7
Other					
Latin America	2.4	0.4	0.1	0.9	0.2
Other	1.1	0.2	0.1	0.4	0.1

eta = -0.8

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	39.5	8.5	5.2	18.6	1.8
Japan	45.9	8.3	3.6	14.3	3.5
Korea	11.3	2.0	0.9	3.6	1.1
Chinese Taipei	5.5	0.9	0.4	1.7	0.5
China	2.1	0.3	0.1	0.6	0.2
India	19.3	3.1	0.8	6.4	1.6
Brazil	7.8	1.5	0.3	3.1	0.5
Other					
Latin America	2.9	0.6	0.1	1.2	0.2
Other	2.5	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	28.2	4.7	2.6	7.6	1.7
Japan	37.3	5.6	2.5	6.9	1.9
Korea	14.6	2.2	1.0	2.7	1.0
Chinese Taipei	2.7	0.4	0.2	0.5	0.2
China	16.4	2.3	0.9	3.0	1.0
India	19.3	2.6	0.7	3.8	1.2
Brazil	8.3	1.3	0.3	2.0	0.6
Other					
Latin America	2.2	0.3	0.1	0.5	0.2
Other	1.4	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	35.5	6.9	2.8	14.6	2.3
Japan	38.9	7.0	2.5	13.5	2.0
Korea	17.7	3.2	1.1	6.2	1.1
Chinese Taipei	5.5	1.0	0.3	1.9	0.3
China	22.1	3.9	1.2	7.6	1.3
India	22.7	3.9	1.0	8.0	1.4
Brazil	8.2	1.5	0.3	3.2	0.7
Other					
Latin America	2.4	0.4	0.1	0.9	0.2
Other	1.1	0.2	0.1	0.4	0.1

TABLE A.5: Stackelberg model: Trade-flows in million tonnes for $eta = -0.7$ to $eta = -0.8$

Source: own analysis.

eta = -0.1

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	26.9	8.1	5.0	14.0	3.1
Japan	27.7	8.3	4.9	13.7	2.9
Korea	6.9	2.1	1.2	3.4	0.8
Chinese Taipei	3.3	1.0	0.6	1.6	0.4
China	1.2	0.4	0.2	0.6	0.1
India	11.5	3.4	1.9	5.7	1.4
Brazil	4.8	1.5	0.8	2.5	0.6
Other					
Latin America	1.8	0.5	0.3	0.9	0.2
Other	1.6	0.5	0.3	0.8	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	16.9	6.5	3.6	8.0	2.1
Japan	20.7	7.9	4.3	9.4	2.2
Korea	8.2	3.1	1.7	3.7	0.9
Chinese Taipei	1.5	0.6	0.3	0.7	0.2
China	9.0	3.4	1.8	4.1	1.0
India	10.6	4.0	2.1	4.8	1.3
Brazil	4.7	1.8	0.9	2.2	0.6
Other					
Latin America	1.2	0.5	0.2	0.6	0.2
Other	0.8	0.3	0.2	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	24.0	6.8	3.8	12.4	2.3
Japan	24.7	7.0	3.9	12.5	2.3
Korea	11.3	3.2	1.8	5.7	1.1
Chinese Taipei	3.5	1.0	0.5	1.8	0.3
China	14.0	3.9	2.2	7.1	1.3
India	14.4	4.0	2.2	7.3	1.4
Brazil	5.4	1.5	0.8	2.8	0.6
Other					
Latin America	1.6	0.4	0.2	0.8	0.2
Other	0.7	0.2	0.1	0.4	0.1

eta = -0.2

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	28.7	8.1	5.1	14.8	2.8
Japan	29.8	8.3	4.9	14.0	3.1
Korea	7.5	2.1	1.2	3.5	0.8
Chinese Taipei	3.6	1.0	0.6	1.7	0.4
China	1.3	0.4	0.2	0.6	0.1
India	12.3	3.3	1.9	5.9	1.5
Brazil	5.2	1.5	0.8	2.6	0.6
Other					
Latin America	1.9	0.5	0.3	1.0	0.2
Other	1.7	0.5	0.3	0.8	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	18.4	6.5	2.1	8.1	2.0
Japan	22.7	7.9	2.4	9.3	2.1
Korea	9.0	3.1	1.0	3.7	0.9
Chinese Taipei	1.6	0.6	0.2	0.7	0.2
China	9.9	3.4	1.0	4.0	1.0
India	11.6	4.0	1.1	4.8	1.3
Brazil	5.1	1.8	0.5	2.2	0.6
Other					
Latin America	1.4	0.5	0.1	0.6	0.2
Other	0.8	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	25.6	6.8	3.9	12.6	2.3
Japan	26.5	7.0	3.9	12.7	2.3
Korea	12.2	3.2	1.8	5.8	1.1
Chinese Taipei	3.7	1.0	0.5	1.8	0.3
China	15.0	3.9	2.2	7.1	1.3
India	15.4	4.0	2.2	7.4	1.5
Brazil	5.8	1.5	0.8	2.8	0.6
Other					
Latin America	1.7	0.4	0.2	0.8	0.2
Other	0.8	0.2	0.1	0.4	0.1

eta = -0.3

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	30.5	8.1	5.3	15.5	2.4
Japan	32.0	8.3	4.9	14.3	3.2
Korea	8.0	2.1	1.2	3.6	0.9
Chinese Taipei	3.8	1.0	0.6	1.7	0.4
China	1.4	0.4	0.2	0.6	0.2
India	13.2	3.3	1.8	6.1	1.6
Brazil	5.6	1.5	0.7	2.7	0.5
Other					
Latin America	2.1	0.5	0.3	1.0	0.2
Other	1.8	0.5	0.3	0.9	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	19.2	6.5	2.1	8.2	1.9
Japan	23.8	7.9	2.5	9.2	2.1
Korea	9.4	3.1	1.0	3.6	0.9
Chinese Taipei	1.7	0.6	0.2	0.7	0.2
China	10.4	3.4	1.0	4.0	1.0
India	12.1	4.0	1.0	4.8	1.3
Brazil	5.4	1.8	0.4	2.2	0.6
Other					
Latin America	1.4	0.5	0.1	0.6	0.2
Other	0.9	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	27.2	6.8	3.9	12.9	2.2
Japan	28.3	7.0	3.9	12.8	2.2
Korea	13.0	3.2	1.8	5.9	1.1
Chinese Taipei	4.0	1.0	0.5	1.8	0.3
China	16.0	3.9	2.1	7.2	1.3
India	16.4	4.0	2.1	7.5	1.5
Brazil	6.1	1.5	0.8	2.9	0.6
Other					
Latin America	1.8	0.4	0.2	0.8	0.2
Other	0.8	0.2	0.1	0.4	0.1

TABLE A.6: Cournot cartel model: Trade-flows in million tonnes for $eta = -0.1$ to $eta = -0.3$

Source: own analysis.

eta = -0.4

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	32.4	8.1	5.4	16.3	2.1
Japan	34.1	8.3	4.9	14.6	3.4
Korea	8.5	2.0	1.2	3.6	0.9
Chinese Taipei	4.1	1.0	0.6	1.7	0.5
China	1.5	0.4	0.2	0.6	0.2
India	14.1	3.3	1.7	6.3	1.6
Brazil	5.9	1.5	0.7	2.9	0.5
Other Latin America	2.2	0.5	0.3	1.1	0.2
Other	1.9	0.5	0.3	0.9	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	19.8	6.5	2.2	8.4	1.7
Japan	24.6	7.9	2.5	9.1	2.0
Korea	9.7	3.1	1.0	3.6	0.9
Chinese Taipei	1.8	0.6	0.2	0.7	0.2
China	10.7	3.4	1.0	4.0	1.0
India	12.6	4.0	1.0	4.8	1.3
Brazil	5.5	1.8	0.4	2.3	0.6
Other Latin America	1.5	0.5	0.1	0.6	0.2
Other	0.9	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	29.1	6.8	2.9	13.6	2.1
Japan	30.4	7.0	2.8	13.3	2.2
Korea	13.9	3.2	1.3	6.1	1.1
Chinese Taipei	4.3	1.0	0.4	1.9	0.3
China	17.2	3.9	1.5	7.5	1.4
India	17.6	4.0	1.4	7.8	1.5
Brazil	6.6	1.5	0.5	3.0	0.6
Other Latin America	1.9	0.4	0.2	0.9	0.2
Other	0.9	0.2	0.1	0.4	0.1

eta = -0.5

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	34.1	8.1	5.6	17.2	1.8
Japan	36.2	8.4	4.9	14.9	3.5
Korea	9.0	2.0	1.2	3.7	1.0
Chinese Taipei	4.3	1.0	0.5	1.8	0.5
China	1.6	0.4	0.2	0.7	0.2
India	15.0	3.2	1.6	6.5	1.7
Brazil	6.3	1.5	0.7	3.0	0.5
Other Latin America	2.3	0.6	0.3	1.1	0.2
Other	2.0	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	20.4	6.5	2.3	8.5	1.5
Japan	25.5	8.0	2.5	9.1	2.0
Korea	10.1	3.1	1.0	3.6	0.9
Chinese Taipei	1.8	0.6	0.2	0.6	0.2
China	11.2	3.4	1.0	3.9	1.0
India	13.1	3.9	0.9	4.8	1.3
Brazil	5.7	1.8	0.4	2.3	0.6
Other Latin America	1.5	0.5	0.1	0.6	0.2
Other	0.9	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	30.7	6.8	2.5	14.1	2.0
Japan	32.2	7.0	2.4	13.6	2.2
Korea	14.7	3.2	1.1	6.2	1.1
Chinese Taipei	4.5	1.0	0.3	1.9	0.3
China	18.2	3.9	1.3	7.7	1.4
India	18.7	4.0	1.1	8.0	1.6
Brazil	7.0	1.5	0.4	3.1	0.6
Other Latin America	2.0	0.4	0.1	0.9	0.2
Other	0.9	0.2	0.1	0.4	0.1

eta = -0.6

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	36.0	8.1	5.7	17.7	1.4
Japan	38.4	8.4	4.9	14.9	3.7
Korea	9.6	2.0	1.2	3.7	1.1
Chinese Taipei	4.6	1.0	0.5	1.8	0.5
China	1.7	0.4	0.2	0.7	0.2
India	15.9	3.2	1.5	6.5	1.8
Brazil	6.7	1.5	0.6	3.1	0.5
Other Latin America	2.5	0.6	0.2	1.1	0.2
Other	2.2	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	21.0	6.5	2.3	8.7	1.4
Japan	26.4	8.0	2.5	9.0	2.1
Korea	10.4	3.1	1.0	3.5	1.0
Chinese Taipei	1.9	0.6	0.2	0.6	0.2
China	11.6	3.4	1.0	3.9	1.1
India	13.5	3.9	0.9	4.8	1.3
Brazil	5.9	1.8	0.3	2.3	0.6
Other Latin America	1.6	0.5	0.1	0.6	0.2
Other	1.0	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	32.1	6.8	2.6	14.5	2.0
Japan	33.7	7.1	2.5	13.9	2.2
Korea	15.4	3.2	1.1	6.4	1.1
Chinese Taipei	4.7	1.0	0.3	1.9	0.3
China	19.1	3.9	1.3	7.8	1.4
India	19.6	4.0	1.1	8.2	1.6
Brazil	7.3	1.5	0.4	3.2	0.6
Other Latin America	2.1	0.4	0.1	0.9	0.2
Other	0.9	0.2	0.1	0.4	0.1

Table A.7: Cournot cartel model: Trade-flows in million tonnes for $eta = -0.4$ to $eta = -0.6$

Source: own analysis.

eta = -0.7

2008	Australia	Canada	Russia	USA	other
Europe and Mediterranean	37.8	8.2	5.8	18.0	1.1
Japan	40.5	8.4	4.8	14.7	3.8
Korea	10.1	2.0	1.2	3.6	1.1
Chinese Taipei	4.9	1.0	0.5	1.7	0.6
China	1.8	0.4	0.2	0.6	0.2
India	16.8	3.2	1.4	6.5	1.9
Brazil	7.0	1.5	0.6	3.1	0.5
Other Latin America	2.6	0.6	0.2	1.2	0.2
Other	2.3	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	other
Europe and Mediterranean	21.6	6.5	2.4	8.8	1.3
Japan	27.3	8.0	2.6	8.9	2.1
Korea	10.8	3.1	1.0	3.5	1.0
Chinese Taipei	2.0	0.6	0.2	0.6	0.2
China	12.0	3.4	0.9	3.8	1.1
India	14.0	3.9	0.8	4.8	1.4
Brazil	6.1	1.8	0.3	2.4	0.6
Other Latin America	1.6	0.5	0.1	0.6	0.2
Other	1.0	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	33.0	6.7	2.6	14.6	1.9
Japan	34.8	7.1	2.5	13.9	2.2
Korea	15.9	3.2	1.1	6.3	1.1
Chinese Taipei	4.9	1.0	0.3	1.9	0.3
China	19.7	3.9	1.3	7.8	1.4
India	20.2	4.0	1.1	8.2	1.6
Brazil	7.5	1.5	0.4	3.2	0.6
Other Latin America	2.2	0.4	0.1	0.9	0.2
Other	1.0	0.2	0.1	0.4	0.1

eta = -0.8

2008	Australia	Canada	Russia	USA	other
Europe and Mediterranean	39.5	8.1	5.5	18.3	0.9
Japan	42.7	8.5	4.5	14.5	3.9
Korea	10.6	2.0	1.1	3.6	1.2
Chinese Taipei	5.1	1.0	0.5	1.7	0.6
China	1.9	0.4	0.2	0.6	0.2
India	17.7	3.2	1.2	6.5	1.9
Brazil	7.3	1.5	0.5	3.1	0.5
Other Latin America	2.7	0.6	0.2	1.2	0.2
Other	2.4	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	other
Europe and Mediterranean	22.2	6.5	2.4	8.9	1.2
Japan	28.3	8.0	2.6	8.8	2.1
Korea	11.1	3.1	1.0	3.5	1.0
Chinese Taipei	2.0	0.6	0.2	0.6	0.2
China	12.4	3.4	0.9	3.8	1.1
India	14.5	3.9	0.8	4.8	1.4
Brazil	6.3	1.8	0.3	2.4	0.6
Other Latin America	1.7	0.5	0.1	0.6	0.2
Other	1.0	0.3	0.1	0.4	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	34.6	6.7	2.6	14.7	1.9
Japan	36.5	7.1	2.5	13.8	2.2
Korea	16.7	3.2	1.2	6.3	1.1
Chinese Taipei	5.1	1.0	0.3	1.9	0.4
China	20.7	3.9	1.2	7.8	1.4
India	21.2	3.9	1.0	8.2	1.6
Brazil	7.9	1.5	0.3	3.2	0.7
Other Latin America	2.3	0.4	0.1	0.9	0.2
Other	1.0	0.2	0.1	0.4	0.1

TABLE A.8: Cournot cartel model: Trade-flows in million tonnes for $eta = -0.7$ to $eta = -0.8$

Source: own analysis.

eta = -0.1

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	33.7	8.1	5.0	10.7	3.1
Japan	34.8	8.3	4.9	10.4	2.9
Korea	8.7	2.1	1.2	2.6	0.8
Chinese Taipei	4.2	1.0	0.6	1.2	0.4
China	1.6	0.4	0.2	0.5	0.1
India	14.4	3.4	1.9	4.3	1.4
Brazil	6.1	1.4	0.8	1.9	0.6
Other					
Latin America	2.3	0.5	0.3	0.7	0.2
Other	2.0	0.5	0.3	0.6	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	21.9	6.1	2.1	6.6	2.2
Japan	26.9	7.4	2.5	7.7	2.2
Korea	10.6	2.9	1.0	3.0	0.9
Chinese Taipei	1.9	0.5	0.2	0.6	0.2
China	11.7	3.2	1.1	3.3	1.0
India	13.7	3.8	1.2	4.0	1.2
Brazil	6.1	1.7	0.5	1.8	0.6
Other					
Latin America	1.6	0.4	0.1	0.5	0.2
Other	1.0	0.3	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	30.1	6.8	3.8	9.3	2.4
Japan	31.1	7.0	3.9	9.4	2.3
Korea	14.2	3.2	1.8	4.3	1.1
Chinese Taipei	4.4	1.0	0.5	1.3	0.3
China	17.6	3.9	2.2	5.3	1.3
India	18.0	4.0	2.2	5.5	1.4
Brazil	6.8	1.5	0.8	2.1	0.6
Other					
Latin America	2.0	0.4	0.2	0.6	0.2
Other	0.9	0.2	0.1	0.3	0.1

eta = -0.2

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	35.7	8.1	5.2	11.6	2.9
Japan	37.4	8.3	4.9	10.7	3.0
Korea	9.3	2.1	1.2	2.7	0.8
Chinese Taipei	4.5	1.0	0.6	1.3	0.4
China	1.7	0.4	0.2	0.5	0.1
India	15.5	3.3	1.9	4.5	1.4
Brazil	6.5	1.5	0.8	2.0	0.5
Other					
Latin America	2.4	0.5	0.3	0.8	0.2
Other	2.1	0.5	0.3	0.7	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	22.8	5.9	2.1	6.8	2.1
Japan	28.3	7.1	2.4	7.7	2.1
Korea	11.2	2.8	1.0	3.0	0.9
Chinese Taipei	2.0	0.5	0.2	0.5	0.2
China	12.3	3.1	1.0	3.3	1.0
India	14.5	3.6	1.1	4.0	1.3
Brazil	6.4	1.6	0.5	1.8	0.6
Other					
Latin America	1.7	0.4	0.1	0.5	0.2
Other	1.1	0.3	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	31.9	6.8	3.6	9.6	2.3
Japan	33.2	7.0	3.6	9.5	2.2
Korea	15.2	3.2	1.7	4.3	1.1
Chinese Taipei	4.7	1.0	0.5	1.3	0.3
China	18.8	3.9	2.0	5.3	1.3
India	19.3	4.0	2.0	5.5	1.4
Brazil	7.2	1.5	0.7	2.1	0.6
Other					
Latin America	2.1	0.4	0.2	0.6	0.2
Other	0.9	0.2	0.1	0.3	0.1

eta = -0.3

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	37.4	8.2	5.3	12.1	2.6
Japan	39.7	8.3	4.9	10.7	3.1
Korea	9.9	2.0	1.2	2.7	0.9
Chinese Taipei	4.8	1.0	0.6	1.3	0.4
China	1.8	0.4	0.2	0.5	0.2
India	16.5	3.3	1.8	4.6	1.5
Brazil	6.9	1.5	0.7	2.1	0.5
Other					
Latin America	2.6	0.5	0.3	0.8	0.2
Other	2.2	0.5	0.3	0.7	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	23.6	5.7	2.2	7.0	1.9
Japan	29.6	6.9	2.4	7.7	2.0
Korea	11.7	2.7	1.0	3.0	0.9
Chinese Taipei	2.1	0.5	0.2	0.5	0.2
China	12.9	2.9	1.0	3.3	1.0
India	15.1	3.4	1.0	4.0	1.2
Brazil	6.7	1.6	0.4	1.9	0.6
Other					
Latin America	1.8	0.4	0.1	0.5	0.1
Other	1.1	0.3	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	33.8	6.8	2.4	10.3	2.3
Japan	35.4	7.0	2.4	10.0	2.2
Korea	16.2	3.2	1.1	4.6	1.1
Chinese Taipei	5.0	1.0	0.3	1.4	0.3
China	20.0	3.9	1.3	5.6	1.3
India	20.5	4.0	1.2	5.9	1.5
Brazil	7.7	1.5	0.4	2.3	0.6
Other					
Latin America	2.2	0.4	0.1	0.7	0.2
Other	1.0	0.2	0.1	0.3	0.1

TABLE A.9: Cournot oligopoly model: Trade-flows in million tonnes for $eta = -0.1$ to $eta = -0.3$

Source: own analysis.

eta = -0.4

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	39.2	8.2	5.1	12.9	2.4
Japan	42.1	8.3	4.4	10.9	3.3
Korea	10.5	2.0	1.1	2.7	0.9
Chinese Taipei	5.0	1.0	0.5	1.3	0.4
China	1.9	0.4	0.2	0.5	0.2
India	17.5	3.3	1.5	4.8	1.6
Brazil	7.3	1.5	0.6	2.2	0.5
Other Latin America	2.7	0.5	0.2	0.8	0.2
Other	2.4	0.5	0.2	0.7	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	24.3	5.5	2.2	7.2	1.8
Japan	30.7	6.7	2.5	7.7	2.0
Korea	12.1	2.6	1.0	3.0	0.9
Chinese Taipei	2.2	0.5	0.2	0.5	0.2
China	13.4	2.8	1.0	3.3	1.0
India	15.7	3.3	1.0	4.1	1.3
Brazil	6.9	1.5	0.4	1.9	0.6
Other Latin America	1.8	0.4	0.1	0.5	0.1
Other	1.1	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	34.6	6.8	2.5	10.9	2.3
Japan	36.5	7.0	2.4	10.5	2.2
Korea	16.7	3.2	1.1	4.8	1.1
Chinese Taipei	5.1	1.0	0.3	1.5	0.3
China	20.7	3.9	1.3	5.9	1.3
India	21.2	4.0	1.2	6.2	1.5
Brazil	7.9	1.5	0.4	2.4	0.6
Other Latin America	2.3	0.4	0.1	0.7	0.2
Other	1.0	0.2	0.1	0.3	0.1

eta = -0.5

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	40.5	8.2	4.8	14.1	2.1
Japan	43.9	8.3	4.0	11.6	3.4
Korea	10.9	2.0	1.0	2.9	1.0
Chinese Taipei	5.3	1.0	0.4	1.4	0.5
China	2.0	0.4	0.2	0.5	0.2
India	18.2	3.2	1.2	5.1	1.6
Brazil	7.6	1.5	0.5	2.4	0.5
Other Latin America	2.8	0.6	0.2	0.9	0.2
Other	2.5	0.5	0.2	0.8	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	24.9	5.4	2.3	7.5	1.7
Japan	31.7	6.6	2.5	7.7	2.0
Korea	12.5	2.6	1.0	3.0	0.9
Chinese Taipei	2.3	0.5	0.2	0.5	0.2
China	13.9	2.8	1.0	3.3	1.0
India	16.2	3.2	0.9	4.1	1.3
Brazil	7.1	1.5	0.4	2.0	0.6
Other Latin America	1.9	0.4	0.1	0.5	0.2
Other	1.2	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	35.6	6.8	2.6	11.5	2.2
Japan	37.8	7.0	2.4	10.9	2.1
Korea	17.2	3.2	1.1	5.0	1.1
Chinese Taipei	5.3	1.0	0.3	1.5	0.3
China	21.4	3.9	1.3	6.1	1.3
India	21.9	4.0	1.1	6.5	1.5
Brazil	8.1	1.5	0.4	2.5	0.6
Other Latin America	2.4	0.4	0.1	0.7	0.2
Other	1.1	0.2	0.1	0.3	0.1

eta = -0.6

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	41.2	8.3	4.7	15.6	1.9
Japan	45.1	8.3	3.6	12.5	3.5
Korea	11.2	2.0	0.9	3.1	1.0
Chinese Taipei	5.4	1.0	0.4	1.5	0.5
China	2.0	0.4	0.1	0.5	0.2
India	18.8	3.2	1.0	5.5	1.7
Brazil	7.8	1.5	0.4	2.7	0.5
Other Latin America	2.9	0.6	0.2	1.0	0.2
Other	2.5	0.5	0.2	0.9	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	25.3	5.4	2.4	7.7	1.6
Japan	32.5	6.6	2.5	7.6	2.0
Korea	12.8	2.6	1.0	3.0	1.0
Chinese Taipei	2.3	0.5	0.2	0.5	0.2
China	14.2	2.8	0.9	3.3	1.0
India	16.7	3.2	0.9	4.1	1.3
Brazil	7.2	1.5	0.4	2.0	0.6
Other Latin America	1.9	0.4	0.1	0.5	0.2
Other	1.2	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	36.3	6.8	2.6	12.2	2.2
Japan	38.6	7.0	2.5	11.5	2.1
Korea	17.6	3.2	1.1	5.3	1.1
Chinese Taipei	5.4	1.0	0.3	1.6	0.3
China	21.9	3.9	1.2	6.5	1.3
India	22.4	4.0	1.1	6.8	1.5
Brazil	8.3	1.5	0.4	2.7	0.6
Other Latin America	2.4	0.4	0.1	0.8	0.2
Other	1.1	0.2	0.1	0.4	0.1

TABLE A.10: Cournot oligopoly model: Trade-flows in million tonnes for $eta = -0.4$ to $eta = -0.6$

Source: own analysis.

eta = -0.7

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	40.9	8.3	4.8	17.4	1.6
Japan	45.3	8.4	3.6	13.8	3.6
Korea	11.2	2.0	0.9	3.4	1.1
Chinese Taipei	5.5	0.9	0.4	1.6	0.5
China	2.0	0.3	0.1	0.6	0.2
India	18.9	3.1	0.9	6.1	1.7
Brazil	7.8	1.5	0.4	3.0	0.5
Other					
Latin America	2.9	0.6	0.1	1.1	0.2
Other	2.5	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	25.9	5.4	2.5	7.9	1.5
Japan	33.4	6.6	2.5	7.6	2.0
Korea	13.1	2.6	1.0	3.0	1.0
Chinese Taipei	2.4	0.5	0.2	0.5	0.2
China	14.7	2.8	0.9	3.3	1.1
India	17.2	3.2	0.8	4.2	1.3
Brazil	7.4	1.5	0.3	2.1	0.6
Other					
Latin America	2.0	0.4	0.1	0.5	0.2
Other	1.2	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	36.1	6.8	2.7	13.4	2.2
Japan	38.7	7.1	2.5	12.5	2.1
Korea	17.6	3.2	1.1	5.7	1.1
Chinese Taipei	5.4	1.0	0.3	1.7	0.3
China	21.9	3.9	1.2	7.0	1.3
India	22.5	3.9	1.0	7.5	1.5
Brazil	8.3	1.5	0.4	2.9	0.7
Other					
Latin America	2.4	0.4	0.1	0.9	0.2
Other	1.1	0.2	0.1	0.4	0.1

eta = -0.8

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	40.6	8.3	5.0	18.4	1.3
Japan	45.5	8.4	3.6	14.4	3.7
Korea	11.2	2.0	0.9	3.6	1.2
Chinese Taipei	5.5	0.9	0.4	1.7	0.5
China	2.1	0.3	0.1	0.6	0.2
India	19.0	3.1	0.9	6.4	1.8
Brazil	7.8	1.5	0.3	3.1	0.5
Other					
Latin America	2.9	0.6	0.1	1.2	0.2
Other	2.5	0.5	0.2	1.0	0.2

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	26.4	5.4	2.5	8.1	1.5
Japan	34.4	6.5	2.6	7.6	2.0
Korea	13.5	2.5	1.0	3.0	1.0
Chinese Taipei	2.5	0.4	0.2	0.5	0.2
China	15.1	2.7	0.9	3.2	1.1
India	17.7	3.1	0.8	4.2	1.3
Brazil	7.6	1.5	0.3	2.1	0.6
Other					
Latin America	2.0	0.4	0.1	0.6	0.2
Other	1.3	0.2	0.1	0.3	0.1

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	35.9	6.8	2.7	14.5	2.1
Japan	38.8	7.1	2.5	13.5	2.1
Korea	17.6	3.2	1.2	6.2	1.1
Chinese Taipei	5.5	1.0	0.3	1.9	0.3
China	22.0	3.9	1.2	7.6	1.4
India	22.5	3.9	1.0	8.1	1.5
Brazil	8.3	1.5	0.3	3.2	0.7
Other					
Latin America	2.4	0.4	0.1	0.9	0.2
Other	1.1	0.2	0.1	0.4	0.1

TABLE A.11: Cournot oligopoly model: Trade-flows in million tonnes for $eta = -0.7$ to $eta = -0.8$

Source: own analysis.

eta = -0.1

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	5.5	13.2	8.1	44.1	0.1
Japan	71.8	0.0	0.0	0.0	0.0
Korea	14.5	0.0	0.0	0.0	3.5
Chinese Taipei	8.6	0.0	0.0	0.0	0.0
China	1.1	0.0	0.0	0.0	2.1
India	29.8	0.0	0.0	0.0	0.0
Brazil	4.0	6.3	0.0	0.0	2.4
Other Latin America	0.6	3.9	0.0	0.0	0.2
Other	1.2	2.2	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	2.7	8.4	33.8	0.3
Japan	54.2	0.0	0.0	0.0	0.0
Korea	19.9	0.0	0.0	0.0	1.6
Chinese Taipei	3.9	0.0	0.0	0.0	0.0
China	22.5	0.0	0.0	0.0	1.1
India	27.8	0.0	0.0	0.0	0.0
Brazil	1.3	8.1	0.0	0.0	3.1
Other Latin America	1.8	1.4	0.0	0.0	0.0
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	52.2	0.0
Japan	48.0	15.0	0.0	0.0	0.0
Korea	27.3	0.0	0.0	0.0	1.6
Chinese Taipei	8.8	0.0	0.0	0.0	0.0
China	33.1	0.0	0.0	0.0	2.5
India	36.6	0.0	0.0	0.0	0.0
Brazil	0.0	11.7	0.0	0.6	1.5
Other Latin America	0.0	1.2	0.0	0.2	2.6
Other	0.1	0.0	0.0	0.9	0.8

eta = -0.2

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	5.8	8.4	8.1	50.4	0.1
Japan	73.9	0.0	0.0	0.0	0.0
Korea	15.0	0.0	0.0	0.0	3.5
Chinese Taipei	8.8	0.0	0.0	0.0	0.0
China	1.2	0.0	0.0	0.0	2.1
India	30.6	0.0	0.0	0.0	0.0
Brazil	0.0	10.5	0.0	0.0	2.5
Other Latin America	0.4	4.4	0.0	0.0	0.1
Other	1.2	2.3	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	3.2	8.4	33.8	0.3
Japan	55.0	0.0	0.0	0.0	0.0
Korea	20.2	0.0	0.0	0.0	1.6
Chinese Taipei	3.9	0.0	0.0	0.0	0.0
China	22.8	0.0	0.0	0.0	1.1
India	28.2	0.0	0.0	0.0	0.0
Brazil	0.0	10.1	0.0	0.0	2.5
Other Latin America	1.3	1.5	0.0	0.0	0.6
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	53.1	0.0
Japan	46.5	17.4	0.0	0.0	0.0
Korea	27.7	0.0	0.0	0.0	1.6
Chinese Taipei	9.0	0.0	0.0	0.0	0.0
China	33.6	0.0	0.0	0.0	2.5
India	37.1	0.0	0.0	0.0	0.0
Brazil	0.0	7.8	0.0	3.2	3.0
Other Latin America	0.0	2.7	0.0	0.2	1.1
Other	0.1	0.0	0.0	0.9	0.8

eta = -0.3

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	5.3	7.9	8.1	52.2	0.1
Japan	74.7	0.0	0.0	0.0	0.0
Korea	14.7	0.0	0.0	0.0	4.0
Chinese Taipei	8.9	0.0	0.0	0.0	0.0
China	1.2	0.0	0.0	0.0	2.1
India	30.9	0.0	0.0	0.0	0.0
Brazil	0.0	13.1	0.0	0.0	0.0
Other Latin America	0.0	2.3	0.0	0.0	2.6
Other	1.2	2.3	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	3.9	8.4	33.8	0.3
Japan	55.2	0.6	0.0	0.0	0.0
Korea	20.5	0.0	0.0	0.0	1.6
Chinese Taipei	4.0	0.0	0.0	0.0	0.0
China	23.2	0.0	0.0	0.0	1.1
India	28.6	0.0	0.0	0.0	0.0
Brazil	0.0	12.0	0.0	0.0	0.8
Other Latin America	0.0	1.0	0.0	0.0	2.3
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	53.7	0.0
Japan	45.3	19.3	0.0	0.0	0.0
Korea	28.0	0.0	0.0	0.0	1.6
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.5	0.0	0.0	0.0	0.0
Brazil	0.0	6.7	0.0	5.3	2.1
Other Latin America	0.0	1.9	0.0	0.2	2.0
Other	0.1	0.0	0.0	0.9	0.8

TABLE A.12: Perfect competition model: Trade-flows in million tonnes for $eta = -0.1$ to $eta = -0.3$

Source: own analysis.

eta = -0.4

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	4.2	7.7	9.8	52.2	0.1
Japan	75.3	0.0	0.0	0.0	0.0
Korea	14.8	0.0	0.0	0.0	4.0
Chinese Taipei	9.0	0.0	0.0	0.0	0.0
China	1.3	0.0	0.0	0.0	2.1
India	31.2	0.0	0.0	0.0	0.0
Brazil	0.0	13.2	0.0	0.0	0.0
Other Latin America	0.0	2.3	0.0	0.0	2.6
Other	1.2	2.3	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	4.5	8.4	33.8	0.3
Japan	54.0	2.6	0.0	0.0	0.0
Korea	20.8	0.0	0.0	0.0	1.6
Chinese Taipei	4.1	0.0	0.0	0.0	0.0
China	23.5	0.0	0.0	0.0	1.1
India	29.0	0.0	0.0	0.0	0.0
Brazil	0.0	11.4	0.0	0.0	1.6
Other Latin America	0.0	1.9	0.0	0.0	1.5
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	53.8	0.0
Japan	45.3	19.3	0.0	0.0	0.0
Korea	28.0	0.0	0.0	0.0	1.6
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.5	0.0	0.0	0.0	0.0
Brazil	0.0	6.6	0.0	5.1	2.5
Other Latin America	0.0	2.1	0.0	0.5	1.6
Other	0.1	0.0	0.0	0.9	0.8

eta = -0.5

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	1.3	8.3	13.0	52.2	0.1
Japan	76.4	0.0	0.0	0.0	0.0
Korea	15.1	0.0	0.0	0.0	4.0
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	1.3	0.0	0.0	0.0	2.1
India	31.6	0.0	0.0	0.0	0.0
Brazil	0.8	12.6	0.0	0.0	0.0
Other Latin America	0.1	2.3	0.0	0.0	2.6
Other	1.2	2.4	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	4.9	8.4	33.8	0.3
Japan	53.3	3.9	0.0	0.0	0.0
Korea	21.0	0.0	0.0	0.0	1.6
Chinese Taipei	4.1	0.0	0.0	0.0	0.0
China	23.8	0.0	0.0	0.0	1.1
India	29.2	0.0	0.0	0.0	0.0
Brazil	0.0	11.5	0.0	0.0	1.5
Other Latin America	0.0	1.9	0.0	0.0	1.6
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	53.9	0.0
Japan	45.6	19.2	0.0	0.0	0.0
Korea	27.6	0.0	0.0	0.0	2.1
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.6	0.0	0.0	0.0	0.0
Brazil	0.0	6.7	0.0	4.9	2.6
Other Latin America	0.0	2.1	0.0	0.5	1.5
Other	0.1	0.0	0.0	0.9	0.8

eta = -0.6

2008	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	8.5	14.6	52.2	0.1
Japan	77.0	0.0	0.0	0.0	0.0
Korea	15.3	0.0	0.0	0.0	4.0
Chinese Taipei	9.2	0.0	0.0	0.0	0.0
China	1.3	0.0	0.0	0.0	2.1
India	31.8	0.0	0.0	0.0	0.0
Brazil	1.1	11.6	0.0	0.0	0.8
Other Latin America	0.0	3.2	0.0	0.0	1.8
Other	1.2	2.4	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	5.2	8.4	33.8	0.3
Japan	52.7	4.9	0.0	0.0	0.0
Korea	21.2	0.0	0.0	0.0	1.6
Chinese Taipei	4.1	0.0	0.0	0.0	0.0
China	24.0	0.0	0.0	0.0	1.1
India	29.5	0.0	0.0	0.0	0.0
Brazil	0.0	10.2	0.0	0.0	3.0
Other Latin America	0.0	3.3	0.0	0.0	0.1
Other	0.4	0.9	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and Mediterranean	0.0	0.0	9.4	53.9	0.0
Japan	45.6	19.2	0.0	0.0	0.0
Korea	27.6	0.0	0.0	0.0	2.1
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.6	0.0	0.0	0.0	0.0
Brazil	0.0	7.8	0.0	4.9	1.4
Other Latin America	0.0	1.0	0.0	0.4	2.7
Other	0.1	0.0	0.0	0.9	0.8

TABLE A.13: Perfect competition model: Trade-flows in million tonnes for $eta = -0.4$ to $eta = -0.6$

Source: own analysis.

eta = -0.7

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	8.0	15.2	52.2	0.1
Japan	77.3	0.0	0.0	0.0	0.0
Korea	15.3	0.0	0.0	0.0	4.0
Chinese Taipei	9.2	0.0	0.0	0.0	0.0
China	1.3	0.0	0.0	0.0	2.1
India	31.9	0.0	0.0	0.0	0.0
Brazil	0.7	10.4	0.0	0.0	2.4
Other					
Latin America	0.0	4.8	0.0	0.0	0.2
Other	1.2	2.4	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	5.8	8.4	33.8	0.3
Japan	51.7	6.6	0.0	0.0	0.0
Korea	21.5	0.0	0.0	0.0	1.6
Chinese Taipei	4.2	0.0	0.0	0.0	0.0
China	24.3	0.0	0.0	0.0	1.1
India	29.8	0.0	0.0	0.0	0.0
Brazil	0.0	10.2	0.0	0.0	3.1
Other					
Latin America	0.0	3.5	0.0	0.0	0.0
Other	0.4	1.0	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	0.0	9.4	53.9	0.0
Japan	45.6	19.2	0.0	0.0	0.0
Korea	27.6	0.0	0.0	0.0	2.1
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.6	0.0	0.0	0.0	0.0
Brazil	0.0	8.0	0.0	4.9	1.2
Other					
Latin America	0.0	0.8	0.0	0.4	2.9
Other	0.1	0.0	0.0	0.9	0.8

eta = -0.8

2008	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	7.9	15.2	52.2	0.1
Japan	77.3	0.0	0.0	0.0	0.0
Korea	15.3	0.0	0.0	0.0	4.0
Chinese Taipei	9.2	0.0	0.0	0.0	0.0
China	1.3	0.0	0.0	0.0	2.1
India	31.9	0.0	0.0	0.0	0.0
Brazil	0.2	10.9	0.0	0.0	2.4
Other					
Latin America	0.4	4.4	0.0	0.0	0.2
Other	1.2	2.4	0.0	0.0	0.8

2009	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	6.2	8.4	33.8	0.3
Japan	51.9	6.9	0.0	0.0	0.0
Korea	21.7	0.0	0.0	0.0	1.6
Chinese Taipei	4.2	0.0	0.0	0.0	0.0
China	24.5	0.0	0.0	0.0	1.1
India	30.1	0.0	0.0	0.0	0.0
Brazil	0.0	10.6	0.0	0.0	2.8
Other					
Latin America	0.0	3.3	0.0	0.0	0.3
Other	0.4	1.0	0.0	0.0	0.8

2010	Australia	Canada	Russia	USA	Other
Europe and					
Mediterranean	0.0	0.0	9.4	53.9	0.0
Japan	45.6	19.2	0.0	0.0	0.0
Korea	27.6	0.0	0.0	0.0	2.1
Chinese Taipei	9.1	0.0	0.0	0.0	0.0
China	34.0	0.0	0.0	0.0	2.5
India	37.6	0.0	0.0	0.0	0.0
Brazil	0.0	7.6	0.0	3.7	2.8
Other					
Latin America	0.0	1.2	0.0	1.7	1.3
Other	0.1	0.0	0.0	0.9	0.8

TABLE A.14: Perfect competition model: Trade-flows in million tonnes for $eta = -0.7$ to $eta = -0.8$

Source: own analysis.

Appendix B

Supplementary Data for Chapter 3

Table B.1: Comparison of actual and simulated trade flows in million tonnes (energy adjusted) for eta= -0.5

	South Africa	*Russia*	*Venezuela*	*Vietnam*	*Indonesia*	*Colombia*	*China*	*USA*	*Australia*	*Poland*	*Norway*
Actual trade flows 2008											
Europe	44	64	3	1	14	32	2	15	2	3	3
North America	1		2		2	31			1		
Latin America	2	1	1		1	8		1	1		
China		1		19	25				1		
Taiwan		1			29		11		19		
Japan	1	11		2	27		11		67		
Korea	1	9		1	26		16		19		
India	12				22		1		1		
South East Asia	2				26	2	1		5		
Total	*64*	*87*	*6*	*23*	*172*	*73*	*42*	*16*	*116*	*3*	*3*
Cournot oligopoly with fringe 2008 (eta = -0.5)											
Europe	21	69			32	25	1		28	5	4
North America	3		5		7	6		9	7		
Latin America	2		4		3	3			3		
China	5			5	13	4	5		11		
Taiwan	7			14	15	6	7		13		
Japan	13	7			27	13	14	22	25		
Korea	9	11			18	8	10		16		
India	6				10	5	4		9		
South East Asia	5			3	11	4	4		9		
Total	*72*	*88*	*9*	*22*	*135*	*74*	*45*	*31*	*121*	*5*	*4*
			Actual					Cournot oligopoly with fringe			
Total seaborne trade			606					606			

Source: IEA (2010a), own calculations.

Appendix C

Supplementary Data for Chapter 4

Proof of Proposition in section 4.2.2: We consider a setup with a national player A which controls two firms which can produce a single commodity x: F_1 (exporter) and F_2 (domestic supplier). Further, there exists a domestic market D and an export market E where x can be sold to (price-taking) customers. Let $x_{1,D}$, $x_{1,E}$ and $x_1 = x_{1,D} + x_{1,E}$ be the supply of F_1 to the domestic market, the supply of F_1 to the export market and its total supply, respectively. The same holds for F_2. C_1 and C_2 are the respective convex cost functions of F_1 and F_2 with $c_1(x_1) = \frac{\partial C_1(x_1)}{\partial x_1} > 0 \ \forall x_1$ and $c_2(x_2) = \frac{\partial C_2(x_2)}{\partial x_2} > 0 \ \forall x_2$. The maximum production capacity of F_1 is limited to K. We assume that the exporter faces a cost disadvantage if supplying the domestic market and that the domestic supplier faces a cost disadvantage if supplying the export market. This cost disadvantage of both firms is represented by constant cost terms $t_{1,D} > 0 \ \forall x_{1,D}$ and $\$ = t_{2,E} > 0 \ \forall x_{2,E}$ for F_1 and F_2, respectively. The cost terms are defined such that $c_1(x_1) + t_{1,D} > c_2(x_2) \ \forall x_1, x_2 \in [0, K]$ and $c_2(x_2) + t_{2,E} > c_1(x_1) \ \forall x_1, x_2 \in [0, K]$ hold. Let further U and V be the volume supplied to the export and the domestic market, with $U = x_{1,E} + x_{2,E}$ and $V = x_{1,D} + x_{2,D}$. The inverse demand functions in both markets are decreasing in volumes.

We consider that A maximises welfare in the domestic market D plus his producer rent from sales to the export market E less costs. His payoff function W_A is:

$$W_A = \int_0^V p_D(V)\mathrm{d}V + p_E(U)U - c_1(x_1) - c_2(x_2) - T(x_1, x_2.$$

In the following, we will compare a setup where A controls F_1 and F_2 and has access to export and domestic markets (*export&domestic setup*) with a setup that only accounts for the export market and A only controlling F_1 (*export-only setup*). We will show that $x_{2,E}$ can actually be greater zero rendering the *export-only setup* inconsistent.

Let μ be the capacity scarcity mark-up (dual variable) associated with the production constraint K for F_1. In case of a binding export capacity constraint K the equilibrium condition for firm A to supply the export market in the *export-only setup* is:

$$p_E(K) = -\frac{\partial p_E(U)}{\partial U}K + c_1(K) + \mu^{*'} \qquad \text{if } x^{*'}_{1,E} = K,\ x^{*'}_{2,E} = 0. \tag{C.1}$$

which simply means that marginal revenue equal marginal costs plus the scarcity rent. Equilibrium conditions for A in the *export&domestic setup* are:

$$p_E(K + x^*_{2,E}) = -\frac{\partial p_E(U)}{\partial U}(K + x^*_{2,E}) + c_1(K) + \mu^* \text{ and} \tag{C.2}$$

$$p_E(K + x^*_{2,E}) = -\frac{\partial p_E(U)}{\partial U}(K + x^*_{2,E}) + c_2(x^*_2) + t_{2,E}$$
$$\text{if } x^*_{1,E} = K.\ x^*_{2,E} > 0. \tag{C.3}$$

From (C.2) and (C.3) we can see that

$$x_{2,E} = \begin{cases} > 0, & \text{if } \mu^* = c_2(x^*_2) + t_{2,E} - c_1(K) \\ = 0, & \text{if } \mu^* < c_2(x^*_2) + t_{2,E} - c_1(K) \end{cases} \tag{C.4}$$

in the *export&domestic setup*. Capacity scarcity is a function of the difference in export supply costs between both firms. In case of $x_{2,E} > 0$, F_2 covers the residual export market demand after F_1's maximum export market supply has been deducted (see Figure C.1). F_2 will start supplying the export market as soon as its marginal export revenue equals marginal costs. In this case, the resulting price bias is:

$$p_E(U^{*'}) - p_E(U^*) = \mu^{*'} - \left(c_2(x^*_2) + t_{2,E} - c_1(K) - \frac{\partial p_E(U)}{\partial U}x^*_{2,E}\right), \tag{C.5}$$

which is always greater zero in the case of a decreasing demand function as total export market supply $U^* = K + x_{2,E}$ in the *export&domestic setup* is greater than export supply in the *export-only setup* $U^{*'} = K$.

The same inconsistency occurs if A acts in a competitive manner in the export market. However, the price bias is even higher: A would not account for the export price reduction inferred by delivering additional supply to the export market if it acts as a price taker. Thus, marginal revenue from supplying the export market equals export price leading to a even higher redirection of domestic supply. In this case, domestic supply to the export market acts as a backstop for export market prices in the case we also consider the domestic market. The price bias in a competitive setup would therefore be:

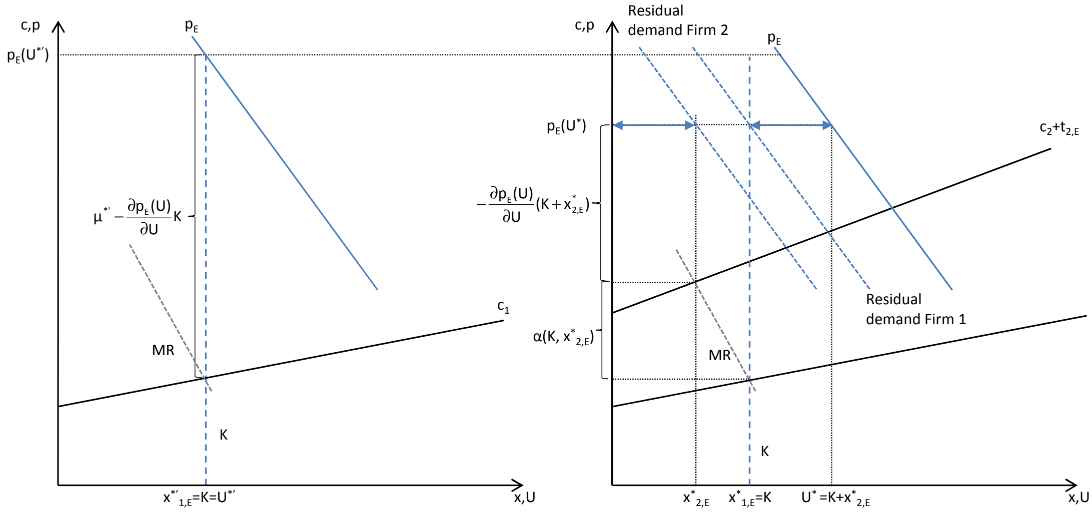

FIGURE C.1: Export market equilibrium for the *export-only setup*(left) vs. *export&domestic setup* (right).

$$p_E(U^{*'}) - p_E(U^*) = \mu^{*'} - \left(c_2(x_2^*) + t_{2,E} - c_1(K)\right). \tag{C.6}$$

Table C.1: Actual and modeled steam coal trade market flows in million tonnes in 2008

	Japan	Korea (S.)	Taiwan	U.S.	China	Europe	India	Other
Actual trade volumes in Mt								
Indonesia	24.4	23.2	23.7	2.1	22.2	19.1	19.0	23.8
Colombia				27.8		35.9		9.5
Australia	74.1	20.5	20.6	0.1	1.7	2.8	0.8	6.2
South Africa	0.1	1.0		0.8		48.2	7.9	3.7
Russia	8.9	6.4	0.9		0.5	68.4		0.6
U.S.	0.3	0.3			0.2	13.5	0.1	4.0
China	11.8	16.7	11.2	0.1		1.7	0.8	1.6
Other	2.0	0.9		2.5	16.8	11.0		7.5
Trade shares for China - Indonesia duopoly without export quota								
Indonesia	16.1	15.9	19.9		38.7	21.5	25.0	23.2
Colombia				25.9		40.0		
Australia	79.3	27.5	23.7					
South Africa			6.4			42.0	14.1	
Russia		23.4				69.3		
U.S.	21.6					10.4		6.5
China	12.6	8.9	6.4			7.3	5.2	2.9
Other			4.1		15.1	15.3		
Trade shares for Indonesia monopoly with export quota								
Indonesia	15.3	15.9	19.9		55.4	19.8	22.9	22.6
Colombia				25.9		40.0		
Australia	93.9		36.6					
South Africa						39.0	22.2	1.3
Russia	12.0	11.4				69.3		
U.S.	8.7					22.9		6.9
China		48.6						
Other			4.1		15.1	14.9		
Trade shares for perfect competition with export quota								
Indonesia	36.7	32.2	64.7		29.3			26.0
Colombia				25.9		40.0		
Australia	77.0					53.5		
South Africa						8.1	54.4	
Russia	23.4					69.3		
U.S.						28.7		9.8
China		48.6						
Other					19.2	12.1		
Trade shares for perfect competition without export quota								
Indonesia	0.5	15.9	65.4		79.9			27.2
Colombia				34.3		31.5		
Australia	58.7					71.8		
South Africa						2.7	59.9	
Russia	23.4					69.3		
U.S.						27.3		11.2
China	55.9	66.1						
Other					19.2	12.1		

Appendix D

Supplementary Data for Chapter 5

Equilibrium conditions

The equilibrium conditions are derived by the first-order derivatives of the Lagrangian L (Karush-Kuhn-Tucker conditions). For the WCM these conditions are then defined by the equations (5.3) to (5.8) found in section 4.3 and the following additional equilibrium conditions (D.1) to (D.5) .

The Lagrangian multipliers $\mu_{m,t}$ and $\mu_{p,t}$ are the shadow prices at mine node m and port node p in period t and represent the costs of an additional unit of steam coal at that node. In equilibrium, the difference between $\mu_{m,t}$ and $\mu_{p,t}$ are the transport costs for transporting one unit of coal between both nodes (if the transport route exists). Equation (D.1) defines the equilibrium condition for inland transport:

$$\mu_{m,t} + d_t \cdot c^T_{a_{(m,p)},t} - \mu_{p,t} \geq 0 \perp T_{a_{(m,p)},t} \geq 0 \qquad \forall m, p, t. \tag{D.1}$$

The shadow prices $\mu_{p,t}$ and $\mu_{i,t}$ differ in equilibrium by bulk carrier transport rates $c^T_{a_{(m,p)},t}$, by port turnover costs $c^P_{p,t}$ and also by the Lagrangian multiplier $\phi_{p,t}$. $\phi_{p,t}$ represents the value of one additional unit of port turnover capacity at port p. $\phi_{p,t}$ can be interpreted as scarcity rent of constrained port capacity. Equation (D.2) gives the equilibrium condition for sea transport between port node p and import node i:

$$\mu_{p,t} + d_t \cdot c^T_{a_{(p,i)},t} + d_t \cdot c^P_{p,t} + \phi_{p,t} - \mu_{i,t} \geq 0 \perp T_{a_{(p,i)},t} \geq 0 \qquad \forall p, i, t. \tag{D.2}$$

The Lagrangian multiplier $\lambda_{m,t}$ gives the value of one additional unit of production capacity. It is non-zero in the case that the capacity restriction (5.3) has no slack; e.g., when production is at the capacity limits. The shadow price $\mu_{m,t}$ is defined by the marginal production costs function $c_{m,t}$ (the first-order derivative of the production cost function $C_{m,t}$) plus $\lambda_{m,t}$ which can be interpreted as the scarcity rent at mine m in period t if the mine is at maximum production. The equilibrium condition for production at mine nodes is defined by the following equation:

$$d_t \cdot c_{m,t}(S_{m,t}) + \lambda_{m,t} - \mu_{m,t} \geq 0 \perp S_{m,t} \geq 0 \qquad \forall m, t. \tag{D.3}$$

In equilibrium, for the case that $I^M_{m,t} > 0$, the sum of shadows prices for capacity over the remaining model horizon $\sum_{\hat{t}=t}^{T} \lambda_{m\hat{t}} + \epsilon_{m,t}$ has to be equal to investment cost $d_t \cdot c^{I,M}_{m,t}$. The shadow price of the maximum mine investment constraint described in equation (5.8) is $\epsilon_{m,t}$. This equilibrium condition ensures that investment costs are always amortised and allows us to interpret $\mu_{m,t}$ as the long-run marginal costs of mine production including costs for capacity expansions. The same holds for the investment equilibrium conditions for ports (D.5). The equilibrium condition for ports does not include a Lagrangian multiplier for maximum investments, as maximum port investments are not constrained. Equations (D.4) and (D.5) define the equilibrium conditions for mine and port capacity investments:

$$d_t \cdot c^{I,M}_{m,t} + \epsilon_{m,t} - \sum_{\hat{t}=t}^{T} \lambda_{m\hat{t}} \geq 0 \perp I^M_{m,t} \geq 0 \qquad \forall m, t, \tag{D.4}$$

and

$$d_t \cdot c^{I,P}_{p,t} - \sum_{\hat{t}=t}^{T} \phi_{p\hat{t}} \geq 0 \perp I^P_{p,t} \geq 0 \qquad \forall p, t. \tag{D.5}$$

Table D.1: Marginal cost data (minimum, maximum and median)

	2005			2030			
in \$2009/t	MC_{min}	MC_{max}	MC_{median}	MC_{min}	MC_{max}	MC_{median}	Predominant mining technology
Queensland OC	14	34	23	27	68	44	Dragline/Truck and Shovel
Queensland UG	23	34	26	45	66	50	Longwalling
New South Wales OC	18	37	25	36	73	50	Dragline/Truck and Shovel
New South Wales UG	20	39	26	38	77	51	Longwalling
South Africa	12	32	21	40	105	56	Dragline/Room and Pillar
Indonesia	13	33	18	45	118	65	Truck and Shovel
Russia Donbass	9	31	19	27	92	56	Longwalling
Russia Kuzbass	9	31	19	27	92	56	Longwalling/Dragline
Colombia	15	22	18	52	76	62	Truck and Shovel
Venezuela	17	26	21	43	64	51	Truck and Shovel
Vietnam	18	27	20	46	70	52	Truck and Shovel
USA - Northern Appalachia	22	50	27	43	97	52	Longwalling
USA - Southern Appalachia	22	50	27	42	96	52	Longwalling/Dragline
USA - Illinois basin	20	35	43	37	65	47	Room and Pillar/Longwalling
USA - Northern PRB	5	15	7	9	28	12	Dragline/Truck and Shovel
USA - Southern PRB	19	32	21	36	60	39	Dragline/Truck and Shovel
China - IMAR	11	34	23	19	58	39	Longwalling
China - Shanxi	17	42	28	31	75	49	Longwalling
China - Shaanxi	14	36	25	25	66	46	Longwalling
China - Henan	14	37	25	27	68	47	Longwalling
China - Shandong	18	38	27	26	66	46	Longwalling
China - Other	14	37	25	27	67	47	Longwalling/Dragline

TABLE D.2: Projected steam coal trade flows in 2020 and 2030 for both scenarios

		2020		2030				2020		2030	
in Mt		by-wire	by-train	by-wire	by-train	in Mt		by-wire	by-train	by-wire	by-train
QLD OC	QLD - port	21.1	27.1	27.5	36.0	Shaanxi/IMAR invest	Shanghai	311.0	0.0	694.9	0.0
QLD UG	QLD - port	7.9	8.4	8.3	8.4	Shaanxi/IMAR invest	Hong Kong	348.9	0.0	564.8	0.0
NSW OC	NSW - port	40.0	53.6	46.2	58.3	Shaanxi/IMAR invest	Beijing	0.0	137.6	0.0	220.6
NSW UG	NSW - port	19.8	26.9	23.1	30.0	Shaanxi/IMAR invest	China - port	0.0	501.5	0.0	999.5
South Africa	South Africa - port	46.4	54.4	33.5	53.1	Xinjiang invest	Shanghai	195.2	0.0	441.9	0.0
Indonesia	Indonesia - port	133.6	171.5	88.5	172.9	Xinjiang invest	Hong Kong	202.6	0.0	312.0	0.0
Russia Donezk	Russia med -port	24.6	25.3	22.5	25.4	Xinjiang invest	China - West	0.0	45.6	5.0	355.9
Russia Kuzbass	Russia pacific - port	1.5	26.7	0.0	44.8	Queensland - port	Taiwan	29.0	35.5	35.7	44.4
Russia Kuzbass	Russia med -port	35.0	20.0	30.8	12.9	NSW - port	Japan	104.4	51.3	97.6	97.6
Colombia	Colombia - port	60.7	60.7	58.7	60.7	NSW - port	South Korea	74.2	0.0	42.1	0.0
Venezuela	Venezuela - port	9.9	9.9	9.9	9.9	NSW - port	Taiwan	0.0	33.9	20.0	0.0
Vietnam	Viet Nam - port	24.2	24.9	24.9	24.9	NSW - port	India - west	9.9	0.0	33.4	0.0
USA - Northern App.	USA - North Atlantic	69.6	69.6	73.7	73.7	NSW - port	India - east	0.0	0.0	25.3	0.0
USA - Northern App.	USA - South Atlantic	63.1	74.5	86.1	122.6	NSW - port	Chile	9.9	9.9	11.0	0.0
USA - Southern App.	USA - Central	80.8	109.8	121.9	179.5	NSW - port	Hong Kong	0.0	145.4	0.0	150.6
USA - Southern App.	USA - South Atlantic	86.4	69.5	73.9	30.2	South Africa - port	NW Europe	82.8	70.2	62.8	0.0
USA - Southern App.	USA port	0.0	0.0	0.0	23.3	South Africa - port	India - west	2.7	36.1	20.1	53.5
USA - Illinois basin	USA - Central	128.5	99.5	99.7	21.5	South Africa - port	India - east	0.0	0.0	0.0	53.5
USA - Illinois basin	USA - SE central	0.9	29.9	29.8	108.0	South Africa - port	Brazil	8.5	8.5	11.1	6.6
USA - Northern PRB	USA - Central	0.0	0.0	0.0	20.7	Indonesia - port	Taiwan	28.0	0.0	0.0	36.2
USA - Northern PRB	USA - NW central	130.4	130.4	138.1	138.1	Indonesia - port	India - west	23.6	0.0	0.0	0.0
USA - Northern PRB	USA - SW central	108.1	108.1	98.4	82.1	Indonesia - port	India - east	36.1	36.1	28.3	0.0
USA - Northern PRB	USA - Western	101.7	101.7	107.8	107.8	Indonesia - port	Other Asia	51.1	51.1	65.5	65.5
USA - Southern PRB	USA - SW central	28.3	28.4	46.1	62.4	Indonesia - port	Hong Kong	0.0	101.8	0.0	88.9
China - IMAR	Beijing	185.0	210.7	228.4	246.1	Russia pacific - port	Japan	0.0	53.1	0.0	0.0
China - Shanxi	Beijing	163.3	0.0	238.3	0.0	Russia pacific - port	South Korea	5.0	0.0	0.0	87.7
China - Shanxi	China - North	361.3	361.3	343.7	484.1	Russia med -port	NW Europe	22.6	2.8	20.6	0.0
China - Shanxi	China - port	16.2	244.3	68.5	178.8	Russia med -port	Med. Europe	62.1	0.0	61.4	0.0
China - Shaanxi	Shanghai	132.2	0.0	0.0	0.0	Colombia - port	Med. Europe	0.0	62.1	0.0	53.2
China - Shaanxi	China - West	0.0	171.1	177.0	177.0	Colombia - port	NW Europe	0.0	5.4	0.0	66.4
China - Henan	Shanghai	193.7	201.7	167.0	202.8	Colombia - port	Chile	0.0	0.0	0.0	11.0
China - Shangdong	China - North	0.0	0.0	140.4	0.0	Colombia - port	USA - SE central	74.1	72.1	71.9	0.0
China - Shangdong	Shanghai	122.5	137.2	0.0	143.6	China - port	South Korea	16.2	95.3	68.5	22.9
China - other	Hong Kong	95.4	318.6	0.0	351.0	China - port	Shanghai	0.0	607.4	0.0	921.5
China - other	China - West	834.6	617.9	936.4	585.4	China - port	Hong Kong	0.0	43.2	0.0	233.8
Australia invest	NSW - port	138.4	160.0	160.0	160.0	USA port	NW Europe	0.0	0.0	0.0	23.3
South Africa invest	South Africa - port	47.6	60.5	60.5	60.5	Venezuela - port	NW Europe	0.0	27.0	20.7	14.4
Indonesia invest	Indonesia - port	5.2	17.6	5.2	17.6	Venezuela - port	Med. Europe	0.0	0.0	0.0	8.2
Russia invest	Russia pacific - port	3.5	26.3	0.0	42.9	Venezuela - port	Brazil	0.0	0.0	0.0	4.5
Russia invest	Russia med -port	25.1	19.6	28.6	14.9	Venezuela - port	USA - SE central	27.0	0.0	6.3	0.0
Colombia invest	Colombia - port	13.3	16.7	13.2	16.7	Viet Nam - port	Taiwan	12.5	0.0	24.9	0.0
USA invest	USA - South Atlantic	14.6	20.1	13.9	21.0	Viet Nam - port	Shanghai	7.5	0.0	0.0	0.0
Venezuela invest	Venezuela - port	17.1	17.1	17.1	17.1	Viet Nam - port	Hong Kong	4.2	24.9	0.0	24.9

TABLE D.3: Projected marginal costs of supply in both scenarios

	2020		2030			2020		2030	
in $\$_{2009}$/t	by-train	by-wire	by-train	by-wire		by-train	by-wire	by-train	by-wire
Queensland OC	50.4	43.9	79.7	56.3	USA - Central	77.4	75.5	93.9	86.4
Queensland UG	57.8	51.3	87.8	64.4	USA - NW central	60.9	60.8	74.6	69.1
New South Wales OG	53.4	46.2	81.9	58.3	USA - South Atlantic	88.4	86.5	106.5	98.9
New South Wales UC	53.4	46.2	74.6	58.2	USA - SE central	94.4	92.5	113.2	105.6
South Africa	50.2	45.4	74.7	59.2	USA - SW central	74.5	74.5	90.1	84.6
Indonesia	53.6	46.7	82.1	61.0	USA - Western	46.1	46.1	57.8	52.4
Russia Donezk	65.5	60.3	93.8	74.6	Beijing	66.9	63.3	97.0	75.8
Russia Kuzbass	45.7	40.5	71.0	51.8	China - North	85.0	81.2	118.0	96.7
Colombia	63.9	63.0	82.7	74.2	Shanghai	88.3	83.3	121.5	84.3
Venezuela	60.8	61.9	81.7	71.8	Hong Kong	92.8	83.3	126.0	84.3
Vietnam	69.8	60.3	100.6	74.2	China - West	81.0	71.5	112.4	108.0
USA - Northern App.	54.7	52.8	68.3	60.7	Australia invest	53.4	46.2	81.9	58.3
USA - Southern App.	57.0	55.1	70.6	63.1	South Africa invest	50.2	45.4	74.6	59.2
USA - Illinois basin	69.2	67.3	84.6	77.1	Indonesia invest	53.6	46.7	82.1	61.0
USA - Northern PRB	26.8	26.7	35.9	30.5	Russia invest	45.7	40.5	71.0	51.8
USA - Southern PRB	37.3	37.3	47.6	42.1	Colombia invest	63.9	63.0	82.7	74.2
China - IMAR	44.5	40.9	70.9	49.7	USA invest	58.3	56.4	72.1	64.5
China - Shanxi	56.7	52.9	85.1	63.7	Venezuela invest	60.8	61.9	81.7	71.8
China - Shaanxi	54.5	45.7	81.5	77.0	Shaanxi/IMAR invest	56.2	83.3	84.6	84.3
China - Henan	60.8	55.8	89.2	52.0	Xinjiang invest	10.5	33.0	30.2	25.7
China - Shandong	55.3	50.3	83.1	59.9	Queensland - port	64.4	57.9	95.1	71.8
China - other	68.9	59.4	98.3	93.9	New South Wales - port	62.2	55.0	91.7	68.1
North Western Europe	101.5	96.7	119.8	110.4	South Africa - port	63.4	58.6	89.7	74.3
Mediterranean Europe	92.9	88.2	121.0	101.8	Indonesia - port	63.3	56.5	93.7	72.7
Japan	89.7	83.4	120.7	97.1	Russia Baltic - port	82.4	78.4	110.9	91.3
South Korea	88.2	84.4	121.4	98.1	Russia Pacific - port	74.0	68.7	103.7	82.4
Taiwan	89.5	83.0	120.3	96.9	Russia med - port	72.1	66.9	101.6	82.4
India west coast	92.9	88.2	116.9	101.8	Colombia - port	68.1	67.3	87.5	79.0
India east coast	91.2	84.4	117.1	100.6	China - port	74.2	70.5	105.5	84.2
Brazil	93.8	89.1	117.8	102.7	USA - port	77.4	76.7	95.7	86.3
Chile	94.5	88.2	114.9	101.9	Venezuela - port	69.7	70.9	90.7	80.7
Other Asia	81.4	74.6	111.8	90.7	Viet Nam -port	76.7	67.2	107.5	81.1
USA - North Atlantic	84.6	82.7	102.2	94.6					

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CURRICULUM VITAE

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EDUCATION

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Study Abroad Programme — **2007**
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University Entrance Examination (Abitur) — **2003**
Freie Waldorfschule Schopfheim — *Schopfheim, Germany*

PROFESSIONAL EXPERIENCE

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Secondee — **May to July 2012**
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Secondee — **July to November 2011**
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Intern — **August to September 2008**
Centre of European Economic Research (ZEW) — *Mannheim, Germany*

Intern — **June to September 2007**
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Archer Daniels Midland Company (ADM) — *Koog a/d Zaan, The Netherlands*

AWARDS

Theodor Wessels Prize — **2011**
Award for outstanding research on energy economics

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