Strategic Behaviour in International Metallurgical Coal Markets[☆]

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Abstract

This paper analyses 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 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 strategic behaviour of coal exporters.

Keywords: metallurgical coal trade, market power, oligopoly, Stackelberg, Cournot

JEL classification: C61, L11, L13, L71, Q31

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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.

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The international metallurgical coal (or coking coal) trade – metallurgical coal is a key input in steelmaking – is another such example.[1] 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.

In the context of the oligopolistic market structure and the high prices in recent years, this 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 (Chang, 1997; Bowden, 2012).

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).[2] 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 and delivery 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-

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[1] 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.

[2] 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).

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 this paper – a Stackelberg model, two varieties of a Cournot model, and a perfect competition model – for computing 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; Kolstad and Abbey, 1984; Haftendorn and Holz, 2010; 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 this 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 paper is organised as follows: section two briefly introduces the international metallurgical coal market. Section three describes the models developed in this paper. The data is presented in section four. The statistical measures used to validate the models are described in section five. Results are shown in section six. Section seven discusses the results and section eight concludes the paper.

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

Table 1: Market shares in the international metallurgical coal trade, 2010

Importers \ *Exporters*	*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: Derived from IEA (2011a), IEA (2010), IEA (2009).

to 227 USD/t in 2010.[3]

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 export capacities and their close location to the main importers.[4] 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.[5]

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

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

[4] 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).

[5] 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).

exclusively seaborne, using dry bulk vessels) in 2010.[6] 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.

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 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%).

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.[7]

The modelling approach for competitive and Cournot-Nash equilibria (sections 3.1 and 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, 1986), 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 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).

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

[7] 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.

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), the role of dominant utilities in the European power system (Gabriel and Leuthold, 2010), or crude oil market power analysis (Huppmann and Holz, 2012) 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 this paper as there is only one dominant player exporting metallurgical coal per country. Importers are assumed to behave as price takers.[8] 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 $i \in I$.[9] In all three models, import demand in region $j \in J$ is represented by a linear function of the form:

$$p_j = P_j\left(\sum_{m \in M} x_{m,j}\right) = a_j - b_j \cdot \sum_{m \in M} x_{m,j} \tag{1}$$

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.

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

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

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

$X_{-i,j}$ as the quantity supplied by all other producers to region $j \in J$:

$$X_{-i,j} = \sum_{m \in M \neq M_i} x_{m,j} \tag{2}$$

Player i's profit maximisation problem Ω_i consists of the profit function (3) and the constraints (4) and (5):

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(X_{-i,j} + X_{i,j} \right) \cdot X_{i,j} - \tau_{m,j} \cdot x_{m,j} - c_m \cdot x_{m,j} \right] \tag{3}$$

subject to:

$$Cap_m \geq \sum_{j \in J} x_{m,j} \quad (\mu_m) \tag{4}$$

$$x_{m,j} \geq 0 \tag{5}$$

Restriction (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 (3) and the convex restrictions (4) and (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:

$$\tau_{m,j} + c_m + \mu_m + b_j \cdot x_{m,j} - \left[a_j - b_j \cdot \left(X_{-i,j} + X_{i,j} \right) \right] \geq 0 \perp x_{m,j} \geq 0 \tag{6}$$

$$- \sum_{j \in J} x_{m,j} + Cap_m \geq 0 \perp \mu_m \geq 0 \tag{7}$$

Equation (1), constraint (5) and the first order conditions (6) and (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.[10]

3.2. Perfect Competition

In the competitive model, the players face a similar optimisation problem as in the Cournot-Nash model, given by (3), (4) and (5), with the exception that the players cannot influence the market price in region

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

$j \in J$. This leads to the following objective function for competitive players:

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(\sum_{m \in M} x_{m,j} \right) \cdot x_{m,j} - \tau_{m,j} \cdot x_{m,j} - c_m \cdot x_{m,j} \right] \tag{8}$$

Given the non-negativity of output condition and constrained production capacity, player i's profit maximisation problem Θ_i consists of profit function (8) and constraints (4) and (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 (6) simplifies to (9) under the assumption of a linear demand function.

$$\tau_{m,j} + c_m + \mu_m - \left(a_j - b_j \cdot \sum_{m \in M} x_{m,j} \right) \geq 0 \perp x_{m,j} \geq 0 \tag{9}$$

FOC (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 (7) and (9) as well as equation (1) and constraint (5) constitute an optimisation problem with a unique solution (see section 3.1) which is implemented in GAMS and solved with PATH. The outcome of the model presented here corresponds to the outcome of a least-cost allocation determined by a benevolent social planner.

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.[11] The leader incurs seaborne freight costs f_j for coal 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 $j \in J$.

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

The leader's profits are characterised by (10) whereas (11) is the mining capacity restriction and (12) states, that only positive output is possible.

$$max_{m\in M_s} \sum_{j\in J} \left[P_j\left(Q_j+Y_j\right)\cdot Q_j - f_j\cdot q_{m,j} - \kappa_m\cdot q_{m,j}\right] \tag{10}$$

$$Cap_m \geq \sum_{j\in J} q_{m,j} \tag{11}$$

$$q_{m,j} \geq 0 \tag{12}$$

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 (3), (4), and (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)) but also on the leader's output decision Q_j. This leads to the following best-response function (13) in its complementarity form:

$$\tau_{m,j} + c_m + \mu_m + b_j\cdot x_{m,j} - \left[a_j - b_j\cdot\left(X_{-i,j} + X_{i,j} + Q_j\right)\right] \geq 0 \perp x_{m,j} \geq 0 \tag{13}$$

The upper-level optimisation problem (10) to (12) and the lower-level optimality conditions for all followers $i \in I$ (7) and (13) as well as inequality (5) and equation (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).[12]

4. Dataset

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 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 or Marston, 2010), annual reports, investment reports, business plans, market reviews (e.g. IEA, 2011b,c), research

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

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.

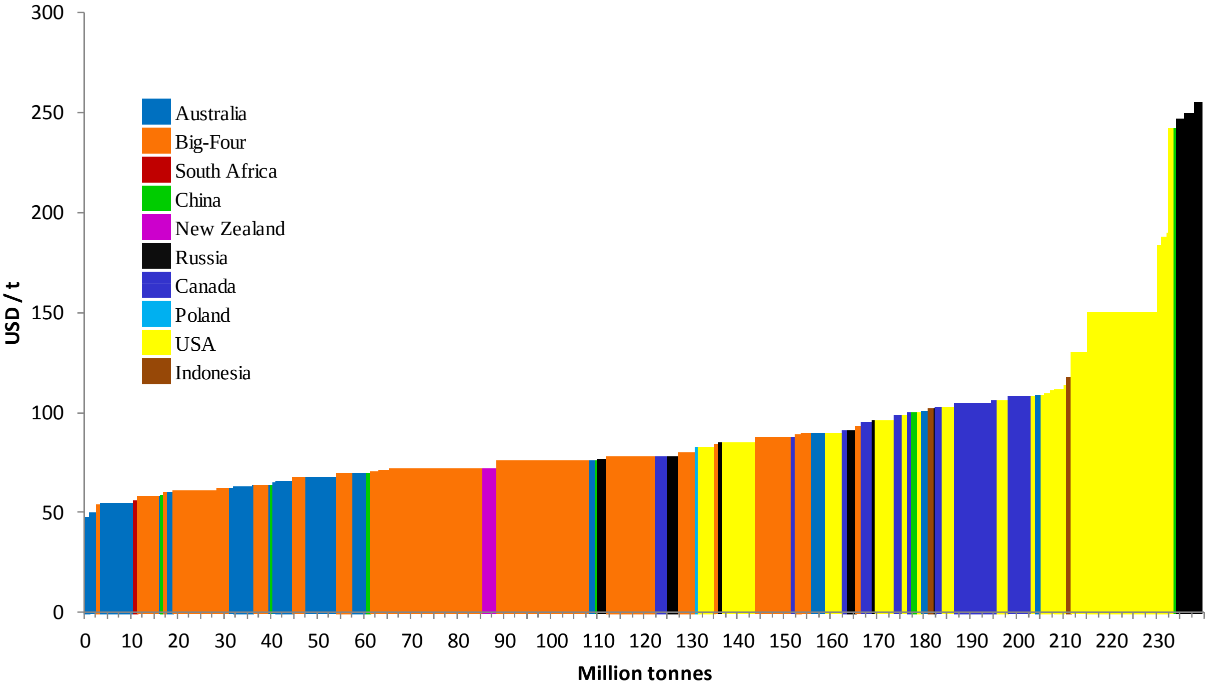

Figure 1: FOB supply cash costs of export mines as implemented in the models, 2008

Source: Own analysis based on CoAL (2009), Franke (2011), Rademacher (2008), Bayer et al. (2009), Rademacher and Braun (2011), Schiffer and Ritschel (2007), Company annual reports (various editions), Company production reports (various editions), IEA (2011b) and IEA (2011c).

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 (see table 2). 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 1 presents the supply cost curve example (FOB) for the year 2008 for all players.[13] Figure 2 gives an overview of how individual cost components contributed to the total FOB cash costs by region.

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

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[13] See appendix for a summary table of supply cost and capacity data by year and player.

Table 2: Share of underground and open-cast mining in export and export-oriented metallurgical coal production

	Australia	Canada	China	Colombia	Poland	Indonesia	New Zealand	Russia	South Africa	USA
Open-cast	78%	100%	0%	0%	0%	100%	100%	58%	0%	37%
Underground	22%	0%	100%	100%	100%	0%	0%	42%	100%	63%

Source: Own analysis based on Schiffer and Ritschel (2007), IEA (2011b), DNRM (2011), ABARES (2008), NSW-DPI (2009), EIA (2010) and EIA (2011) .

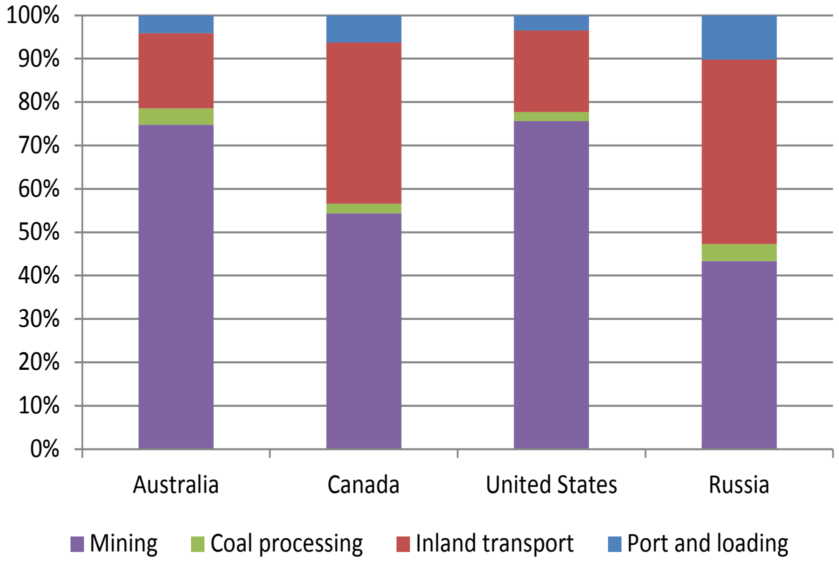

Figure 2: Average contribution of cost components to FOB supply cash costs by region, 2008

Source: Own analysis based on Meister (2008), IEA (2011b), IEA (2011c), Baruya (2007), Schiffer and Ritschel (2007).

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.[14] The individual transport cost functions were calculated for every year. These freight cost parameters are used in the model to determine consistent freight rates for every possible shipping route.

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 characterised 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 3). 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

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[14] See appendix for the parameters and the t-statistics of the OLS estimation.

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 this 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 3: 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).

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).[15] 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:

$$U = \frac{\sqrt{\sum_{k \in K} (X_k - A_k)^2}}{\left(\sqrt{\sum_{k \in K} {X^2}_k} + \sqrt{\sum_{k \in K} {A^2}_k}\right)} \tag{14}$$

As can be seen in (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

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

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} (16), its variance proportion U_{VAR} (17), and its bias proportion U_{BIAS} (18) using the mean-squared-error MSE (15).

$$MSE = \sum_{k \in K} (X_k - A_k)^2 + (\sigma_X - \sigma_A)^2 + 2 \cdot (1 - r_{XA}) \cdot \sigma_X \cdot \sigma_A \tag{15}$$

$$U_{COV} = 2 \cdot (1 - r_{XA}) \cdot \sigma_X \cdot \sigma_A / MSE \tag{16}$$

$$U_{VAR} = (\sigma_X - \sigma_A)^2 / MSE \tag{17}$$

$$U_{BIAS} = \sum_{k \in K} (X_k - A_k)^2 / MSE \tag{18}$$

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 trade flows X_k:

$$A_k = \beta_0 + \beta_1 \cdot X_k + \epsilon_k \tag{19}$$

I estimate equation (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

$$rho = 1 - \sum_k d_k^2/(n^3 - n) \tag{20}$$

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.

6. Results

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.[16] With regard to Theil's inequality coefficient and its covariance proportion, two observations stand out (figure 3): 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.

The analysis of Spearman's *rho* supports the above findings (figure 3). 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 4). 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

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[16] Trade-flow matrices for mid-range *etas* can be found in the appendix. Trade-flows for other elasticities are available from the author upon request.

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.

Table 4: 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 ' '.

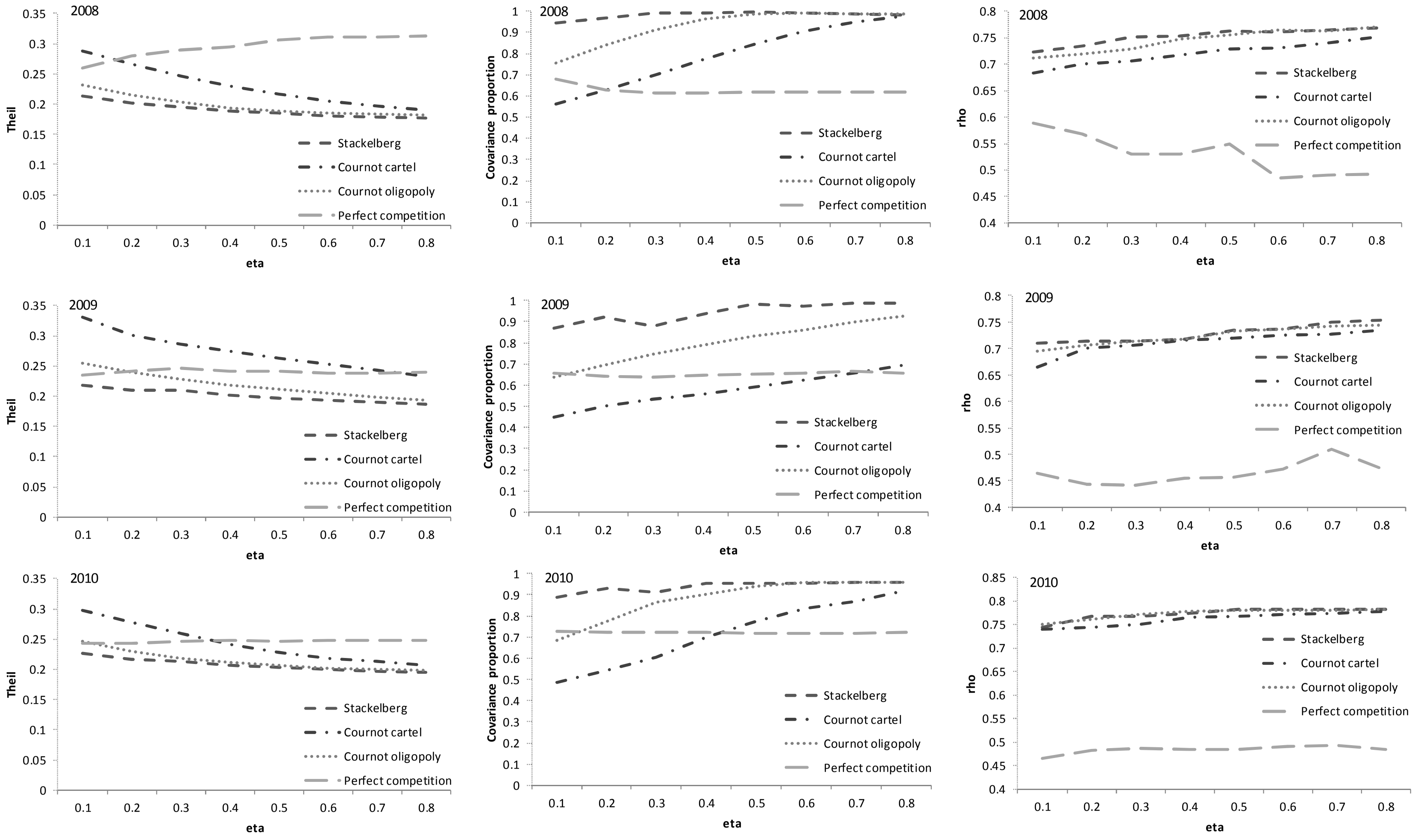

Figure 3: Theil's inequality coefficient and the covariance proportion as well as Spearman's *rho* as functions of *eta*

Source: Own calculations.

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 4).[17] 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.

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[17] 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.

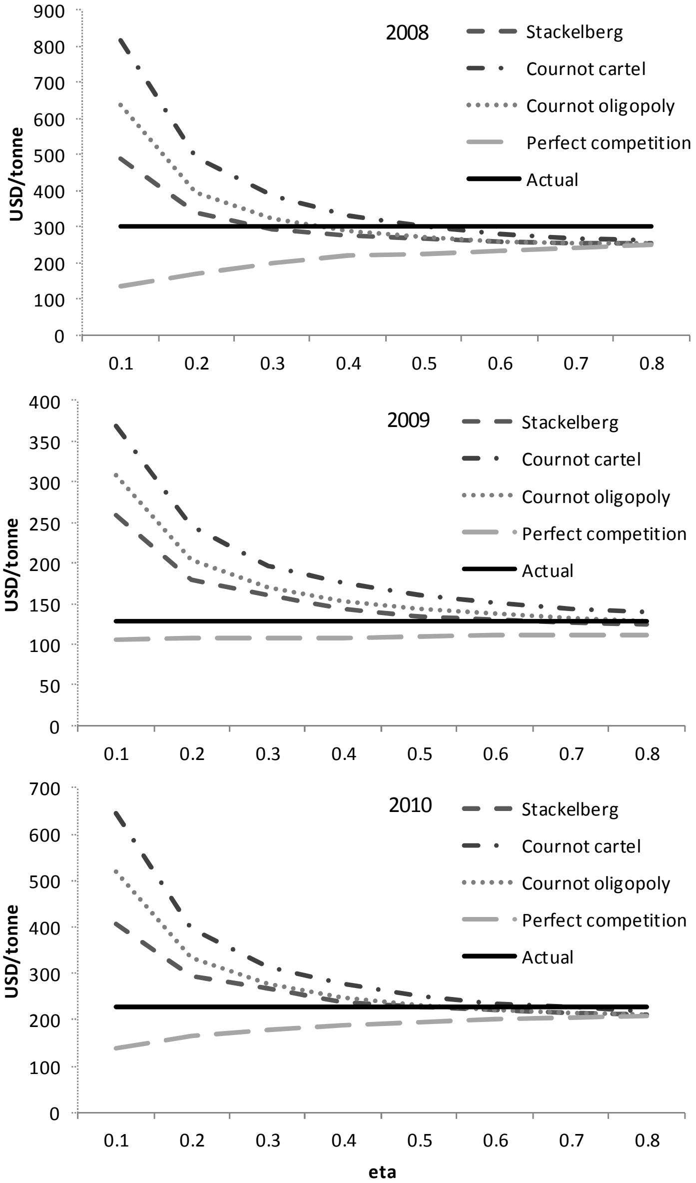

Figure 4: Model-based prices as a function of *eta* and real market benchmark price

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

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 5). 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 4) but the expansion in sales overcompensates this effect for the leader, rendering this strategy profitable.

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 6) 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 scenario, yet short of capacity they are constrained to the corresponding Cournot output (table 6).

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.[18] 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.

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[18] Given Cournot competition, collusion (or a horizontal merger) has two opposite effects: cartelisation reduces the number of players in the market and hence reduces competition. This effect leads to higher industry profits. However, the combined players get a relatively smaller share of the industry profit. Whether collusion is profitable thus depends on the magnitude of the two effects.

Table 5: 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.

Table 6: 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.

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 this 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.

8. Conclusions

Three optimisation models for typical resource markets were developed in this 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 this paper, modeling 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.

Appendix

Computational details

The model described in section 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, n.d.). 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 (n.d.) with the MPEC described in this paper, and identify candidates that produce satisfactory solutions.[19] Although there are several more, a set of five key options essentially defines the reformulation method applied.[20] 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 7 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.[21] 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 .

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[19] 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.

[20] The description of the reformulation methods in this section closely follows GAMS (n.d.).

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

Table 7: 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

Test model for optimal follower behaviour

To test for ex-post optimal follower behaviour in the Stackelberg model, objective function (3) and inequalities (4) and (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 3.3), and $X_{i,j}^{test} = \sum_{m \in M_i} x_{m,j}^{test}$ being the output decision of the test problem.

$$max_{m \in M_i} \sum_{j \in J} \left[P_j \left(Z_j^{MPEC} + X_{i,j}^{test} \right) \cdot X_{i,j}^{test} - \tau_{m,j} \cdot x_{m,j}^{test} - c_{m,j} \cdot x_{m,j}^{test} \right] \tag{3a}$$

Subject to:

$$Cap_m \geq \sum_{j \in J} x_{m,j}^{test} \tag{4a}$$

$$x_{m,j}^{test} \geq 0 \tag{5a}$$

Quasi-concave equation (3a) and linear inequalities (4a) and (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 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 $x_{m,j}^{test} = x_{m,j}^{MPEC}$.

Supplementary data

Table 9 provides an overview of the supply cost and capacity dataset as implemented in the models. A comparison of the 2010-median FOB-cost values in table 9 to the cost curve displayed in IEA (2011c, p.407) reveals that the two datasets are generally well in line. The IEA (2011c) cost curve draws on different sources than the curves used in this paper and is therefore well suited for an unbiased comparison. However, one has to keep in mind that the curve in IEA (2011c) presents *average* FOB-costs of *utilised* capacity. The two datasets will therefore naturally differ to some degree. Hence, the comparison should focus on the relative position of a player along the global cost curve and whether the average FOB-cost value differs *significantly* from the median cost value. In this respect the IEA (2011c) cost curve is widely consistent with the median FOB-cost values in table 9. This is especially true for the large suppliers Australia, Canada and the United States. Russian FOB costs are slightly lower in IEA (2011c) as compared to the median cost value in table 9. China, South Africa and New Zealand are also consistent. The datasets only differ significantly with regard to Mozambique, Vietnam, and Indonesia – tiny players in the international metallurgical coal trade. Mozambique only started exporting in late 2011 and is therefore irrelevant for the analysis in this paper. Vietnam is not included in this paper as Vietnamese exports are often not classified as metallurgical coal in official statistics. However, in principle, some Vietnamese high-ash anthracite coal can be used as PCI coal after processing. Colombia and Indonesia are similar cases where it is debatable whether their exports are indeed metallurgical coal but a fraction of their coal sales is often specified as metallurgical coal in export statistics (see e.g. IEA, 2011a). For consistency reasons the data in this paper exclusively follows the classification of metallurgical coal exports as in IEA (2011a).

Table 8 presents the parameters and t-statistics for the OLS estimation of the freight cost functions. Distances between ports were calculated using the distance calculator on www.searates.com.

Table 8: Freight cost function parameters and t-statistics

	2008	2009	2010
γ	0.4771	1.4681	2.2012
φ	0.4806	0.2731	0.2406
n	13	9	14
t-value	8.067***	4.201**	2.700 .

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

Table 9: Supply cost and capacity data summary

		2008	2009	2010
Big-Four	FOB-cost range in USD/t	54 - 93	55 - 95	56 - 97
	FOB-cost median in USD/t	72	73	75
	Capacity in mt	100	100	111
	Production sites	20	20	23
Other Australia	FOB-cost range in USD/t	48 - 109	49 - 111	50 - 114
	FOB-cost median in USD/t	64	65	66
	Capacity in mt	37	34	43
	Production sites	21	21	24
Canada	FOB-cost range in USD/t	78 - 108	79 - 110	81 - 113
	FOB-cost median in USD/t	100	101	104
	Capacity in mt	26	28	28
	Production sites	10	11	11
China	FOB-cost range in USD/t	59 - 190	65 - 194	62 - 198
	FOB-cost median in USD/t	70	71	73
	Capacity in mt	4	2	2
	Production sites	7	4	4
Colombia	FOB-cost range in USD/t	0	78	80
	FOB-cost median in USD/t	0	78	80
	Capacity in mt	0	1	2
	Production sites	0	1	1
Poland	FOB-cost range in USD/t	83 - 110	85 - 112	0
	FOB-cost median in USD/t	91	93	0
	Capacity in mt	0	0	0
	Production sites	2	2	0
Indonesia	FOB-cost range in USD/t	102 - 118	104 - 120	106 - 123
	FOB-cost median in USD/t	110	112	115
	Capacity in mt	2	2	3
	Production sites	2	2	3
New Zealand	FOB-cost range in USD/t	72	73	75
	FOB-cost median in USD/t	72	73	75
	Capacity in mt	3	3	3
	Production sites	1	1	1
Russia	FOB-cost range in USD/t	77 - 255	79 - 260	81 - 266
	FOB-cost median in USD/t	99	101	103
	Capacity in mt	15	16	16
	Production sites	10	11	11
South Africa	FOB-cost range in USD/t	35 - 56	36 - 57	37 - 58
	FOB-cost median in USD/t	46	46	47
	Capacity in mt	1	1	1
	Production sites	2	2	2
United States	FOB-cost range in USD/t	83 - 188	76 - 172	78 - 176
	FOB-cost median in USD/t	109	99	102
	Capacity in mt	52	57	60
	Production sites	22	22	22
Total	Capacity in mt	240	243	267
	Production sites	97	97	102

Source: Own analysis based on CoAL (2009), Franke (2011), Rademacher (2008), Bayer et al. (2009), Rademacher and Braun (2011), Schiffer and Ritschel (2007), Company annual reports (various editions), NSW-DPI (2009), NSW-GOV (2010), DNRM (2011), Company production reports (various editions), ABARES (2008), IEA (2011b) and IEA (2011c).

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 10: Real market trade-flows in million tonnes

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

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 11: Stackelberg model: Trade-flows in million tonnes $eta = -0.4$ to $eta = -0.6$

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 12: Cournot cartel model: Trade-flows in million tonnes $eta = -0.4$ to $eta = -0.6$

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 13: Cournot oligopoly model: Trade-flows in million tonnes $eta = -0.4$ to $eta = -0.6$

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 14: Perfect competition model: Trade-flows in million tonnes $eta = -0.4$ to $eta = -0.6$

Source: Own analysis.

References

ABARES, 2008. Minerals and energy - major development projects. Tech. rep., Australian Bureau of Agricultural and Resource Economics and Sciences.

Abbey, D. S., Kolstad, C. D., 1983. The structure of international steam coal markets. Natural Resources Journal 23, 859–892.

ABS, 2006. Producer and international trade price indexes: concepts, sources and methods. Tech. rep., Australian Bureau of Statistics.

Ball, K., Loncar, T., 1991. Factors Influencing the Demand for Australian Coal. Tech. rep., ABARE - Australian Government Publishing Service, Canberra.

Bard, J., Plummer, J., Sourie, J., 2000. A bilevel programming approach to determining tax credits for biofuel production. European Journal of Operational Research 120, 30–46.

Baruya, P., 2007. Supply costs for internationally traded steam coal. Tech. rep., IEA Clean Coal Centre.

Bayer, A., Rademacher, M., Rutherford, A., 2009. Development and perspectives of the Australian coal supply chain and implications for the export market. Zeitschrift für Energiewirtschaft 2, 255–267.

BLS, 2011. Producer price index.
URL `http://www.bls.gov/data/`

Bowden, B., 2012. A history of the Pan-Pacific coal trade from the 1950s to 2011: Exploring the long-term effects of a buying cartel. Australian Economic History Review Vol. 52 (1), 1–22.

Bushnell, J. B., 2003. A mixed complementarity model of hydrothermal electricity competition in the Western United States. Operations Research 51 No.1, 80–93.

Bushnell, J. B., Mansur, E. T., Saravia, C., 2008. Vertical Arrangements, Market Structure, and Competition: An Analysis of Restructured US Electricity Markets. American Economic Review 98(1), 237–266.

Chang, H. S., 1997. Coking Coal Procurement Policies of the Japanese Steel Mills: Changes and Implications. Resources Policy 23 Vol.3, 125–137.

Chen, Y., Hobbs, B. F., Leyffer, S., Munson, T. S., 2006. Leader-follower equilibria for electric power and NOx allowances markets. Computational Management Science 3 (4), 307–330.

CoAL, 2009. Coal Of Africa Limited: International Roadshow - May/June 2009.
URL `http://www.coalofafrica.com/IMG/pdf/2009-0520_CoAL_global_roadshow_FINAL_May_09-2.pdf`

Dirkse, S. P., Ferris, M. C., 1999. Reformulation: non-smooth, piece-wise smooth, semi-smooth and smoothing methods. Kluwer Academic Publishers, Applied Optimization, Ch. Modeling and Solution Environments for MPEC: GAMS and MATLAB, pp. 127–147.

DNRM, 2011. Coal industry review 2010-2011 statistical tables. Tech. rep., Queensland Government Department of Natural Resources and Mines.

EIA, 2010. Annual coal report 2010. Tech. rep., Energy Information Administration/Department of Energy.

EIA, 2011. Annual coal production and consumption data by state. Tech. rep., Energy Information Administration/Department of Energy.

Ferris, M. C., Dirkse, S. P., Meeraus, A., 2002. Mathematical programs with equilibrium constraints: Automatic reformulation and solution via constrained optimization.

Ferris, M. C., Munson, T. S., 1998. Complementarity problems in GAMS and the PATH solver. Journal of Economic Dynamics and Control 24, 2000.

Franke, M., 2011. Eine Untersuchung aktueller Entwicklungen auf dem weltweiten Kokskohlenmarkt. Master's thesis, University of Cologne, Cologne.

Gabriel, S., Leuthold, F. U., 2010. Solving discretely-constrained MPEC problems with applications in electric power markets. Energy Economics 32 (1), 3–14.

GAMS, n.d. Nlpec solver manual. Tech. rep., General Algebraic Modeling System Development Corporation.
URL `http://www.gams.com/dd/docs/solvers/nlpec.pdf`

Graham, P., Thorpe, S., Hogan, L., 1999. Non-competitive market behaviour in the international coking coal market. Energy Economics 21, 195–212.

Haftendorn, C., Holz, F., 2010. Modeling and analysis of the international steam coal trade. The Energy Journal 31 (4), 205–230.

Harker, P. T., 1984. A variational inequality approach for the determintation of oligopolistic market equilibrium. Mathematical Programming 30, 105–111.

Harker, P. T., 1986. Alternative models of spatial competition. Operations Research 34 No. 3, 410–425.

Harker, P. T., Pang, J. S., 1988. Existence of optimal solutions to mathematical programs with equilibrium constraints. Operations Research Letters 7, 61–64.

Hobbs, B., 2001. Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. IEEE Transactions on Power Systems 16 (2), 194–202.

Holz, F., von Hirschhausen, C., Kemfert, C., 2008. A strategic model of European gas supply (GASMOD). Energy Economics 30, 766–788.

Huppmann, D., Holz, F., 2012. Crude Oil Market Power – A Shift in Recent Years? The Energy Journal 33(4), preprint.

IEA, 2009. Coal Information 2009. IEA Publications.

IEA, 2010. Coal Information 2010. IEA Publications.

IEA, 2011a. Coal Information 2011. IEA Publications, Paris.

IEA, 2011b. Medium Term Coal Market Report 2011. IEA Publications, Paris.

IEA, 2011c. World Energy Outlook. IEA Publications, Paris.

Kolstad, C. D., Abbey, D. S., 1984. The effect of market conduct on international steam coal trade. European Economic Review 24, 39–59.

Kolstad, C. D., Burris, A. E., 1986. Imperfectly competitive equilibria in international commodity markets. American Journal of Agricultural Economics 68, 27–36.

Luo, Z.-Q., Pang, J. S., Ralph, S., 1996. Mathematical Programs with Equilibrium Constraints. Cambridge University Press.

Marston, 2010. Marston Associates, The Competitive Cost of Coal: Analyzing the Major Producing Areas of the World. In: Presentation at 16th Annual Coaltrans Asia Conference, 31 May 2010, Bali.

McCloskey, G., 2009. Coal Report Issue 222, Petersfield, United Kingdom.

McCloskey, G., 2011. Coal Report Issue 254, Petersfield, United Kingdom.

McCloskey, G., 2012a. Coal Report Issue 287, Petersfield, United Kingdom.

McCloskey, G., 2012b. Coal Report Issue 286, Petersfield, United Kingdom.

McCloskey, G., 2012c. Coal Report Issue 277, Petersfield, United Kingdom.

Meister, W., 2008. Cost trends in coal mining. In: Coaltrans 2008.

NSW-DPI, 2009. 2009 New South Wales Coal Industry Profile. NSW Department of Primary Industries.

NSW-GOV, 2010. New South Wales Coal Industry Profile 2010. Tech. rep., New South Wales Government.

Paulus, M., Trüby, J., 2011. Coal lumps vs. electrons: How do Chinese bulk energy transport decisions affect the global steam coal market? Energy Economics 33(6), 1127–1137.

Rademacher, M., 2008. Development and perspectives on supply and demand in the global hard coal market. Zeitschrift für Energiewirtschaft 32, 67–87.

Rademacher, M., Braun, R., 2011. The impact of the financial crisis on the global seaborne hard coal market: Are there implications for the future? Zeitschrift für Energiewirtschaft 2, 89 –104.

Rutherford, T. F., 1994. Extensions of GAMS for complementary problems arising in applied economic analysis. Tech. rep., Department of Economics, University of Colorado.

Salant, S. W., Switzer, S., Reynolds, R., 1983. Losses from Horizontal Merger: The Effects of an Exogenous Change in Industry Structure on Cournot-Nash Equilibrium. The Quarterly Journal of Economics 98, No. 2, 185–199.

Samuelson, P. A., 1952. Spatial price equilibrium and linear programming. The American Economic Review 42, 283–303.

Schiffer, H.-W., Ritschel, W., 2007. World Market for Hard Coal 2007. RWE.

Takayama, T., Judge, G. G., 1964. Equilibrium among spatially separated markets: a reformulation. Econometrica 32, 510–524.

Takayama, T., Judge, G. G., 1971. Spatial and temporal price and allocation models. North-Holland, Amsterdam [u.a.].

Theil, H., 1961. Economic forecasts and policy. North-Holland.

Tirole, J., 1988. The Theory of Industrial Organization. MIT Press.

Trüby, J., Paulus, M., 2012. Market structure scenarios in international steam coal trade. The Energy Journal Vol. 33, No. 3,, 91–123.

VDKI, 2011. Jahresbericht 2010/2011. Tech. rep., Verein der Kohleimporteure.

Wolak, F. A., Kolstad, C. D., 1988. Measuring relative market power in the Western U.S. coal market using Shapley values. Resources and Energy 10, 293–314.

Yang, C. W., Hwang, M. J., Sohng, S. N., 2002. The Cournot competition in the spatial equilibrium model. Energy Economics 24, 139–154.

Zhuang, J., Gabriel, S. A., 2008. A complementary model for solving stochastic natural gas market equilibria. Energy Economics 30, 113–147.