The Economics of International Coal Markets

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Abstract

In the scope of four related essays this thesis analyses the Chinese domestic coal sector and coal trade policies and their respective impact on international steam coal trade economics. In particular, the thesis investigates the role of domestic transport infrastructure investment policies as well as Chinese coal export and import controls and the potential exertion of market power through such trade instruments. For this purpose, several spatial equilibrium models have been developed that enable simulation runs to compare different policy scenarios. These models also permit ex-post analyses to empirically test hypotheses of non-competitive market conduct of individual players under the assumption of Cournot behaviour. These model-based analyses yield, among others, the following findings:

If coal is converted into electricity early in the Chinese energy supply chain, worldwide marginal costs of supply are substantially lower than if coal is transported via railway. This can reduce China's dependence on international imports significantly. Allocation of welfare changes, particularly in favor of Chinese consumers while rents of international producers decrease.

If not only seaborne trade but also interactions and feedbacks between domestic coal markets and international trade markets are accounted for, trade volumes and prices of a China - Indonesia duopoly fit the real market outcome best in 2008. Real Chinese export quotas have been consistent with simulated exports under a Cournot-Nash strategy.

Uncertainties with regard to future Chinese coal demand and coal sector policies generate significant costs for international investors and lead to a spatial and temporal reallocation of mining and infrastructure investments. The potential exertion of Chinese demand side market power would further reduce the overall investment activity of exporters.

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Nomenclature

ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABS	Australian Bureau of Statistics
ANFO	Ammonium Nitrate Fuel Oil
APEC	Asia-Pacific Economic Cooperation
APX	Amsterdam Power Exchange
ARA	Amsterdam, Rotterdam, Antwerp
AU	Australia
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
CAPM	Capital Asset Pricing Model
CCII	China Coal Information Institute
CIF	Cost, Insurance, Freight
CMR	Chinese Ministry of Railways
CO	Colombia
CO_2	Carbon Dioxide
DIME	Dispatch and Investment Model for Electricity Markets in Europe
EEX	European Energy Exchange
EIA	Energy Information Administration
EU	Europe
EUR	EURO
EWI	Energiewirtschaftliches Institut an der Universität zu Köln (Institute of Energy Economics at the University of Cologne)
FOB	Free On Board
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product

HVDC	High Voltage Direct Current
IEA	International Energy Agency
IMAR	Autonomous Republic of Inner Mongolia
IMF	International Monetary Fund
IN	India
IR	Indonesia
JA	Japan
KKT	Karush-Kuhn-Tucker Conditions
KR	South Korea
LA	Latin America
LNG	Liquefied Natural Gas
LRMC	Long Run Marginal Costs
MCP	Mixed Complementarity Problem
MIT	Massachusetts Institute of Technology
MJ	Mega Joule
MSE	Mean Squared Error
mt	million (metric) tonnes
mtce	million tonnes of coal equivalent (energy content of 7000kcal/kg)
mtpa	million (metric) tonnes per annum
MWh	Mega Watt hour
NBS	Chinese National Bureau of Statistics
NDRC	Chinese National Development and Reform Commission
NSW	New South Wales (Australia)
NW	Norway
OA	Other Asia
OC	Open Cast
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PC	Perfect Competition
PL	Poland
PRC	People's Republic of China
QLD	Queensland (Australia)
RMSPE	Root Mean Squared Percentage Error
RU	Russian Federation

SA	South Africa
t	(metric) tonne
TRCSC	Chinese Taxation Regulation Commission of the State Council
TW	Taiwan
U.S.	United States
UG	Underground
USD	United States Dollar
VE	Venezuela
VN	Vietnam
VPI	Value of Perfect Information

Chapter 1

Introduction

1.1 Motivation

Strategic trade and resource policies have been known to exist in energy resource markets for decades. The most prominent example is the formation of OPEC in 1960 and the ensuing oil crises in the '70s. After a return to relative calm waters during the '80s and '90s, the first decade of the new millennium has seen strong price increases and high price volatility, not only for oil, but as well for gas and coal.

The unprecedented price shocks for steam coal[1] since 2007 and 2008 have been a truly novel phenomena in a market which had been characterised by long-term contracts, stable prices and practically nonexistent financial markets (IEA, 2011b, Ritschel, 2011). Until recently, the actual international steam coal trade was practically negligible, as most of it was directly used in mine-mouth coal-fired power plants or in other parts of the same nation. Seaborne steam coal trade in 1985 accounted for only 142 mt, or 5%, of global production.

However, international trade has grown significantly in recent years, reaching almost 600 mt in 2010 (IEA, 2011a). The majority of growth took place in the Pacific portion of the market. The main driver behind this evolution has been the rapidly growing demand for energy in South-East Asian economies, most importantly in China. Coal is of pivotal importance to the Chinese energy system, as around 80% of electricity generation and 65% of primary energy demand are coal based. Due to rapid economic growth, hard coal demand in China almost tripled between 2000 and 2010. While Chinese coal reserves

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[1] 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.

are officially plentiful, mining operations have moved further inland and pits are getting deeper due to rapid exploitation of the best deposits.

China has been evolving into a key player in the global coal market, first as an exporter, and then, since the market shaking shift in 2009, as the second largest importer of steam coal. Chinese steam coal production and consumption reached 2700 mt and 2800 mt in 2010, respectively, almost five times the size of global steam coal trade market. Thus, diminutive changes in the domestic Chinese coal market can leverage strongly with global trade markets which potentially increases volatility of international coal prices. There are several current developments in the Chinese coal sector that affect coal demand and might have strong effects on imports and exports: The Chinese coal industry is undergoing a period of large-scale consolidation, during which several so-called *coal power bases* are established throughout coal bearing provinces by the major state-owned mining companies each with more than 100 mt of production capacity (Wuyuan and Peng, 2011). Also, the Chinese government plans the large-scale exploitation of the most Western coal resources in the province of Xinjiang, which also might have significant repercussions on Chinese imports once these new capacities are available. The possible range of future imports or exports is thus very broad and highly uncertain and depends on the amount of future economic growth, energy efficiency and energy diversification in China (IEA, 2011c).

Another development which affects Chinese imports and exports is its tight control over trade streams which the Chinese government established several years ago. Coal exports have been subject to an export quota and special export licenses which are determined by the government on a biannual level. Import taxes have reached 17% for foreign coal shipments in 2010 and are also revised frequently. Such trade controls can also be found for several other key resources, such as the famous rare earths. Additionally, the Chinese government has proclaimed that it plans to introduce similar controls for gas and oil in the near future (IEA, 2011b).

Several questions regarding the global coal market economics arise from this situation which will be investigated in the scope of this thesis. Firstly, how are Chinese imports and exports affected by domestic coal sector policies? How strongly does this feed back into global trade market prices? This question is of special importance to many OECD countries such as the UK, Germany, Japan or South Korea that procure the overwhelming majority of their coal needs on the global trade market. Secondly, does the tight Chinese control of imports and exports serve conservation of its domestic coal resources or maximisation of national rent inflows from resource exports? As the largest steam coal producer and consumer by far and as one of the major players in steam coal trade with a partly state-owned coal industry, China has significant potential to exert market power. Thirdly, How are investments of other major coal exporters affected by uncertain future Chinese import and export developments and potential exertion of market power? Even though Asian coal demand is most likely going to grow further, the higher price volatility due to Chinese import fluctuations makes it more risky to invest into fixed long-term assets, such as coal export facilities and mines.

1.2 Modelling spatial market equilibria

In the scope of this thesis, it is analysed how Chinese coal sector policies and market conduct assumptions affect global coal markets. We estimate the impact of such policies by investigating their implications for the equilibrium of the global coal market. A major characteristic of the global coal market which affects equilibrium in a fundamental way is the spatial separation of coal supply and demand and the associated transport costs. Costs for inland transportation and seaborne haulage can easily make up more than 50% of total costs of coal supply (see Figure 1.1). This makes it essential to respect the spatial economics while analysing coal markets. A common approach to analysing the impact of policy changes or market power is to use spatial equilibrium modelling techniques.

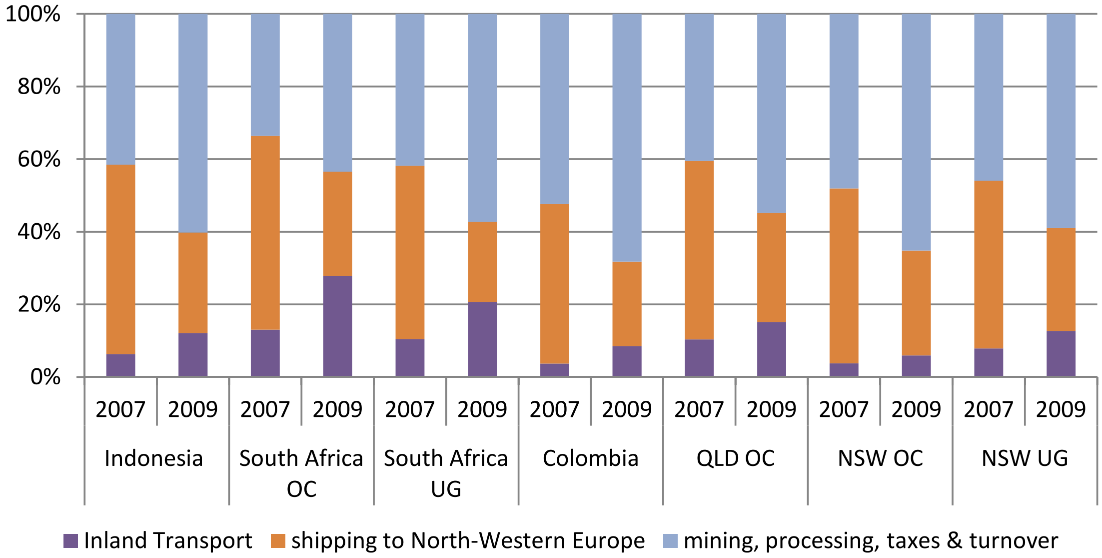

FIGURE 1.1: Breakdown of coal supply costs to North-Western European ports (Source: IEA, 2011b).

Modelling spatial market equilibria has been an active area of research since the early 1950s[2]. First discussions focussed on solving transportation problems with fixed demand and supply, applying the, at this time, modern methods of linear programming

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[2] A comprehensive discussion of spatial market modelling for commodity goods can be found in (Labys and Yang, 1997).

(Hitchcock, 1941, Kantorovich, 1942, Koopmanns, 1949). Enke (1951) provided a framework for solving the spatial equilibrium using analogies from load flow laws. Samuelson (1952) showed in a seminal work that Enke's model could be cast into a mathematical programme by maximising net social payoff and that the dual variables of the programme could be interpreted as equilibrium prices. He also showed that, in the case that demand is a fixed point, minimising transport costs yields the same solution as maximising net social payoff. This case yields the classical Hitchkock-Kantorovich-Koopmanns transport problem known from textbook literature (Dantzig, 1963):

$$\begin{array}{lllll} \min_{x_{ij}} & \sum_{ij} t_{ij} x_{ij} & & & \\ \text{s.t.:} & \sum_j x_{ij} \leq a_i, & \sum_i x_{ij} \geq b_j, & x_{ij} \geq 0, \end{array}$$

where a_i is the capacity constraint of plant i, b_j is demand in market j, t_{ij} are the transportation costs between i and j and x_{ij} are the transport flows. Takayama and Judge (1964) reformulated Samuelson's model to a case where demand and supply costs where not constant but described by linear functions. They showed that the spatial equilibrium can be derived by solving a quadratic programme and provided a discussion of existence, regularity and uniqueness of the solution. This advance significantly expanded application possibilities and a rich stream of empirical analyses, mostly from the agricultural and energy sector, followed[3].

However, spatial modelling techniques had thus far assumed a competitive behaviour of all market actors which was perceived to be often not a good representation of real market conduct. Modelling non-competitive markets required other methods than optimisation techniques, as they do not allow to solve optimisation problems of multiple market players simultaneously. Advances in algorithms dating back to Lemke (1965) led to an increasing usage of complementarity models in spatial economics as they are able to specifically account for strategic behaviour of individual players. Complementarity models exploit the duality concept of the complementary slackness condition in mathematical programmes (Cottle et al., 1992). These models enable one to simultaneously solve the optimisation problems of several market players by directly formulating and solving a set of equilibrium conditions which are derived from the Lagrangian of the original problem. The vector which solves the bundled equilibrium conditions of all players represents the equilibrium for the market. The complementarity formulation has shown to be immensely useful in economic analysis as it provides a tractable framework for oligopolistic competition and other (non-) cooperative games. In spatial market economics, Kolstad and Abbey (1984) and Kolstad and Burris (1986) were among the first to use the linear complementarity approach to solve non-cooperative simultaneous-move

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[3] For an overview of empirical analyses see for example (Labys, 1999).

games in agricultural and resource markets. Harker (1986a) provided a general framework for modelling spatial non-cooperative n-player games as linear complementarity problems (LCP) and described appropriate solution procedures.

LCPs and non-linear complementarity problems (NLCP), problems which include non-linear inequalities, belong to a broader class of problems called mixed complementarity problems (MCP). This class encompasses also problems which include not only inequalities but also equations. In its generalised form, MCPs can be understood as sets of variational inequalities and a significant amount of research has been committed to this field regarding existence, uniqueness, and sensitivity of solutions (Harker and Pang, 1990). An MCP is defined as:

$$\begin{array}{ll}
\text{Given:} & f : \mathbb{R}^N \to \mathbb{R}^N, \quad l, u \in \mathbb{R}^N, \\
\text{Find:} & z, w, v \in \mathbb{R}^N, \\
\text{s.t.:} & F(z) - w + v = 0, \\
 & l \leq z \leq u, \quad w \geq 0, \quad v \geq 0, \\
 & w^T(z - l) = 0, \quad v^T(u - z) = 0,
\end{array}$$

and $-\infty \leq l \leq u \leq +\infty$ (Rutherford, 1995). Several conditions must be satisfied in order to guarantee solvability with state-of-the-art methods[4]. The advantage of the MCP format is that it can express a broad range of economic problems. For example, the reformulation of the classical transport problem in MCP format is:

$$\begin{array}{llll}
\sum_j x_{ij} \leq a_i, & \lambda_i \geq 0, & \lambda_i \left(a_i - \sum_j x_{ij}\right) = 0, & \forall i, \\
\sum_i x_{ij} \leq b_j, & \mu_j \geq 0, & \mu_j \left(b_j - \sum_i x_{ij}\right) = 0, & \forall j, \\
\lambda_i + t_{ij} \geq \mu_j, & x_{ij} \geq 0, & x_{ij} \left(\lambda_i + t_{ij} - \mu_j\right) = 0, & \forall i, j,
\end{array}$$

where λ_i is the dual variable for the capacity constraint and μ_j is the dual variable for the demand constraint. The LCP of the linear programming problem thus directly states the equilibrium condition that will hold if the associated optimisation programme is solved. This means, in this case, that in the competitive equilibrium demand prices equal prices in the supply node plus transport costs if $x_{ij} \geq 0$. However, it would be of limited use to apply the complementarity format for problems which can be expressed as optimisation programmes, a property which Takayama and Judge (1971) call an *integrable* model. Especially in the linear case, algorithms can usually solve optimisation programmes much faster. A typical example of an economic model which is not *integrable* is a non-cooperative spatial market game in which suppliers simultaneously set their quantities

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[4] Among others, F has to be continuously differentiable. Sufficient conditions for convergence of algorithms place additional restrictions on F (see: Harker and Pang, 1990).

á la Cournot. The maximisation problem for each player i in such a setting can be formulated as:

$$\begin{array}{ll} \max_{x_{ij},x_i} & \sum_j p_j \left(\sum_{i'} x_{i'j}\right) x_{ij} - C_i(x_i) - \sum_j t_{ij} x_{ij} \\ s.t.: & \sum_j x_{ij} \leq x_i \qquad (\lambda_i), \end{array}$$

where p_j is a monotonically decreasing continuous inverse demand function of market j, x_i is the production volume of i and C_i is a non-decreasing continuous cost function. As each player i has to solve this maximisation problem simultaneously, the solution to this market game cannot be derived by a single optimisation problem. However, the game can be solved in its complementarity format by deriving the equilibrium conditions from the Lagrangian of each player's optimisation problem:

$$\begin{array}{lll} \sum_j x_{ij} \leq x_i, & \lambda_i \geq 0, & \lambda_i \left(\sum_j x_{ij} - x_i\right) = 0, \\ p_j(.) \leq -\frac{\partial p_j(.)}{\partial x_{ij}} x_{ij} + t_{ij} - \lambda_i, & x_{ij} \geq 0, & x_{ij} \left(p_j(.) + \frac{\partial p_j(.)}{\partial x_{ij}} x_{ij} - t_{ij} + \lambda_i\right) = 0, \quad \forall j \\ -C'(x_i) - \lambda_i \leq 0, & \lambda_i \geq 0, & x_i \left(-C'(x_i) - \lambda_i\right) = 0. \end{array}$$

The well-known feature of the Cournot model is the zero conjectural variation assumption $\frac{\partial x_{i'j}}{\partial x_{ij}} = 0$ for all $i \neq i'$. In this case the term $\frac{\partial p_j(.)}{\partial x_{ij}}$ simplifies to $p_j' \left(\sum_{i'} x_{i'j}\right)$, which is nothing other than the slope of the inverse demand function. The solution to the game is given by the vector that solves the equilibrium conditions for all players simultaneously. The solution in this case is a *Nash equilibrium*, as no player has the incentive to individually deviate from its chosen strategy. The complementarity format thus is a powerful tool to model strategic behaviour in markets. Due to the existence of efficient solution algorithms (e.g.: Ferris and Munson, 1998), this format has been used in many recent empirical market structure studies as for example in Graham et al. (1999), Chen et al. (2006), Lise and Krusemann (2008) or Egging et al. (2010).

Several arguments support that the Cournot assumption is quite appropriate for investigating market conduct in the global coal market: Assuming competition in volumes seems to be appropriate because mining companies manage their collieries by setting production targets and several large national players such as China and Indonesia issue coal production and export volume targets which their domestic coal industries have to meet (or not exceed). While mid- to long-term contracts exist, their share has been dwindling in recent years as especially China sells and procures only on spot markets. The absence of such dominating long-term index-priced contracts, as can be found in natural gas market, also speaks for competition in volumes.

The simultaneous move assumption also is appropriate, because until now no individual coal market player has achieved such a dominant market position in which he knows and also processes the reaction functions of all other players ex-ante as required by a sequential-move game setup.

Other researchers such as Abbey and Kolstad (1983) and Haftendorn and Holz (2010) followed a similar argumentation and also relied on the Cournot model for analysing the coal market's structure in their works. In the scope of the Chapters 3 to 5, which focus on the analysis of market conduct, we will therefore test for Cournot competition in the global coal trade.

1.3 Thesis outline

The main part of the thesis consists of four essays which are all analysing different facets of the impact of Chinese coal sector policy on global coal market economics. Each essay is represented by a chapter and can be read fairly independently, although they are related to each other.

The essay in Chapter 2 covers a scenario analysis for different coal transport strategies in China and possible repercussions on world trade using a dynamic equilibrium model. It has been published in (Paulus and Trüby, 2011) and I have been the leading author of the paper.

Chapters 3 and 4 are interlinked, as they both contain a static analysis of non-competitive coal market behaviour. This strand of research was developed jointly with Johannes Trüby. In Chapter 3, we conduct a market structure analysis which focuses on the main exporters of the international steam coal trade market. The corresponding paper is (Trüby and Paulus, 2011) and I have been a contributing author. In Chapter 4, we expand our previous market structure analysis as we also include domestic coal markets and differing test scenarios. This approach expands results from Chapter 3 and yields some interesting conclusions regarding the economic consistency of Chinese export quota volumes. This work has been published in (Paulus et al., 2011) and I have been the leading author of the paper.

Chapter 5 is based on the former market power analyses and expands them to a dynamic setting. In this essay, I investigate the impact of uncertain future imports and potential market power on investment decisions of other market players. This essay has been published in (Paulus, 2012) and I am the sole contributor. The main body of the thesis is organised as follows:

In the essay in Chapter 2: Coal lumps vs. electrons: How do Chinese bulk energy transport decisions affect the global steam coal market?, we demonstrate 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. An increase in Chinese demand for steam coal will lead to a growing need for additional domestic infrastructure as production hubs and demand centres are spatially separated. Coal transport has so far been mostly handled by railways. However, railway transportation becomes more and more costly as mining operations move to the west of China, due to the cheapest deposits getting exhausted. If domestic railway transport capacity is available only at elevated costs, Chinese power generators may turn to the global trade markets and increase steam coal imports. Increased Chinese imports could then yield significant changes in steam coal market economics on a global scale. Applying direct current electricity transmission in combination with mine-mouth coal-fired power plants could potentially reduce Chinese coal supply costs and make investments into rich, yet very distant coal deposits in the west of China attractive. In fact, the 11th and 12th Five-Year Plan of China already features plans to transport electricity, not mass. Nevertheless, these plans do not seem to have been pursued in earnest until today. To analyse the impact of this transport strategy, we conduct a scenario analysis and compare a setting in which coal is mainly transported by railway with a setting in which coal energy is transported in the form of electricity to assess the long-term change of costs in the coal sector. For this purpose, we develop a spatial equilibrium model for the global steam coal market. The model is dynamic in the sense that we project the coal market until 2030 in both scenarios and that we account for endogenous capacity investments. Costs of capacity investments have to be covered by the sum of future discounted scarcity rents. The market is represented as a network in which supply regions, demand hubs, and export terminals are represented by nodes and transport routes by arcs. The model delivers the cost minimal allocation of investments and the corresponding dispatch of coal trade flows. One major finding is that when coal is converted into electricity early in the supply chain, worldwide marginal costs of supply are lower than when coal is transported via railway. Furthermore, China's dependence on international imports is significantly reduced in this context. Allocation of welfare changes particularly in favour of Chinese consumers while rents of international producers decrease. However, to give a good chance of rapid realisation of such a large-scale national infrastructure project, the national government would have to cut into the well-established web of local decision makers and form a central energy planning institution which has enough executive power.

The discussion in Chapter 3: Market structure scenarios in international steam coal trade, deals with the non-competitive market behaviour of players in the steam coal trade market. Several market fundamentals changed in the last years, which may have lead to the exertion of market power; demand has grown fast, important new players have emerged, and since 2007 prices have increased significantly and remained relatively high. Several nations have started to tighten their control of their coal exports and consortia consisting of large multinational mining companies control vital bottlenecks in the global coal supply chain. We analyse static spatial steam coal trade market equilibria during the years 2006 and 2008. We test for two possible market structure scenarios: perfect competition and an oligopoly setup with major exporters simultaneously competing in quantities (Cournot-Nash strategies). For modelling oligopolistic behaviour, we derive the Kuhn-Tucker conditions and insert a term in the pricing equation of each oligopolist which accounts for its conjecture about how exports of other players change, given a change in its own output. We then compare price levels and trade flows with the reference values in both years. We find that 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 yet not able to reproduce real market outcomes in 2008. The analysis shows that not all available supply capacity was utilised in 2008. The elasticity analysis also confirms that a Cournot market structure for trade market players is not able to explain the market outcome in 2008 satisfactorily. However, objections regarding competition in steam coal trade remain; 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. We conclude that either unknown capacity bottlenecks or more sophisticated non-competitive strategies were the cause for the high prices in 2008.

In Chapter 4: NATIONS AS STRATEGIC PLAYERS IN GLOBAL COMMODITY MARKETS: EVIDENCE FROM WORLD COAL TRADE, we expand upon our analysis from Chapter 3 by explicitly accounting for integrated seaborne trade and major domestic markets and testing different non-competitive setups. 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 expanding the model from Chapter 3 to an equilibrium model which is able to model coal producing nations as strategic players who maximise a payoff function which is the sum of producer and consumer surplus plus export revenues. The model also implements a true graph theory design in which path variables are used to represent individual players' flows through the network. The global steam coal market is then simulated under several imperfect market structure setups focusing on the non-competitive market behaviour of China and Indonesia, two of the largest players in the market with the tightest control on export regimes. Using several non-parametrical tests and other statistics to validate model results we find that trade flows and prices in a China - Indonesia duopoly fit the real market outcome best. Additionally, real-world Chinese export quotas in 2008 were consistent with simulated exports under a Cournot-Nash strategy. Our analysis also shows that China has the potential to act as a cushion against global coal demand shocks, were it to act competitively. However, we can reject the assumption of perfect competition. China may pursue a trade policy of withholding domestic capacity from the global market, driving up international coal prices and avoiding domestic price increases. Thus, it is crucial to account not only for coal trade markets, but also for the domestic markets respecting their interactions and feedbacks if one analyses potential market power in global commodity markets.

In the essay in Chapter 5: HOW ARE INVESTMENT DECISIONS IN THE STEAM COAL MARKET AFFECTED BY DEMAND UNCERTAINTY AND BUYER-SIDE MARKET POWER?, we analyse how profitablity of new investments of international mining companies may be affected through uncertain future Chinese coal consumption and coal imports. we develop a dynamic multi-stage stochastic equilibrium model which is able to simulate investments under uncertainty and market power á la Cournot. Main coal exporting countries are modelled as investors which have to decide on investments into coal export capacities before Chinese coal demand is revealed. Risky demand is represented in extensive form, meaning it can be represented through a scenario tree. We specifically account for risk aversion on the exporter's side by letting them price the systematic risk of their investments consistent with CAPM theory. Haurie et al. (1990) showed that such a stochastic equilibrium programming approach yields a special class of strategies which the authors call *S-adapted open-loop*. This solution concept is situated between the open-loop and the closed-loop equilibrium solution and, while it is still not subgame perfect, can be useful in analysing long term supply and demand decisions under uncertainty without running into the computational challenges of determining closed-loop strategies. The *S-adapted open-loop* concept has been employed in several recent articles, such as (Genc et al., 2007) or (Pineau and Murto, 2003). Using this stochastic investment model, we investigate a scenario in which China behaves as a price taker and another scenario where China exerts market power. As China has changed to become one of the largest net importers of coal since 2009, we focus on the effects of demand side market power (although supply side market power is accounted for). We find that accounting for Chinese demand uncertainty generates significant costs for investors compared to the perfect foresight benchmark and also leads to a spatial and temporal reallocation of investments. If we also account for Chinese demand side market power, overall investment activity is lower. Furthermore, the value of perfect information for China increases if it behaves as a monopolistic player as investments become more costly in the stochastic model due to the risk aversion of investors.

Chapter 2

Coal lumps vs. electrons: How do Chinese bulk energy transport decisions affect the global steam coal market?

2.1 Introduction

Steam coal[5] sourcing and costs have not presented a real challenge during the last decades. However, this situation could change. The center of gravity and price setting in the global steam coal trade market have been shifting to Asia since 2005 (Ritschel, 2011). 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[6]. Established energy projections show that Chinese demand will rise by 80% to 130% until 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

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[5] Steam coal is hard coal of bituminous and sometimes subituminous or anthracite quality which is almost exclusively used in electricity generation.

[6] 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, 2011a).

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 centers around Beijing, Hong Kong 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 centers. Approximately 60% of Chinese coal output was hauled via railway along distances of more than 500 kilometers to coal-fired power plants in 2005 (CCII, 2006). Transport costs make up more than half of delivered costs for domestic coal in the southern provinces. Chinese demand centers 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 foreign steam coal imports (Ritschel, 2011).

Future Chinese steam coal demand can be satisfied either through additional domestic steam coal production or by significantly 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 centers. Unfortunately, large-scale deployment has so 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 (APERC, 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 (Wuyuan and 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 and inefficient coal mines, thus improving economies of scale (NDRC, 2007, Zhao and Creedy, 2008). Consequently, the share of small coal mines in total domestic production dropped significantly from 19.9% (342 mt) in 2003 to 2.1% (55 mt) in 2008 (CCII, 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 might as well 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 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 parameters, 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 reference years 2005 and 2006. Then, two scenarios for possible future transport infrastructure investment decisions in China are investigated: one scenario assumes further investment in railroad transport to move coal energy to the demand centers. 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 paper is structured to include seven sections: after a round-up of relevant literature regarding supply cost modelling and coal market analyses in section two, the current situation in the steam coal trade market will be shortly described in section three. Then, the model is introduced in section four. Section five describes the underlying dataset. Section six depicts the scenario assumptions, and section seven reports model results. Section eight concludes the paper.

2.2 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 (Ritschel, 2011). 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) combines 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 classical Cournot model. They demonstrate that, in the case of heterogeneous demand and cost functions, the spatial Cournot competition model is represented by a linear complementary program (LCP).

One research venue on steam coal market economics has centered on analysing market conduct either in the global trade market (which only accounts for a fraction of the total world wide market) or in regional markets. Abbey and Kolstad (1983) and Kolstad and Abbey (1984) analyse strategic behaviour in international steam coal trade in the early 1980s. In both articles, the authors' model demonstrates an instance of a mixed complementary problem (MCP), derived from the Karush-Kuhn-Tucker conditions that the modelled market participants face and a series of market clearing conditions. In addition to perfect competition, they model different imperfect market structures. Labys and Yang (1980) develop 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 where they model exporting countries in a first scenario as Cournot players and in a second scenario as competitive players. They found no evidence that exporting countries 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) develop a multi-period network flow model for a one-year time period in the integrated energy system in the United

States. They model system-wide energy flows, from the coal and natural gas suppliers to the electric load centers 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 investigate in a case study the lifecycle costs and environmental effects for transporting coal-based energy between the Powder River Basin (Wyoming) to 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) describe 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 significantly improvements over conventional overland transport. There has been no apparent 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 this paper is to understand how different future bulk energy transport configurations for China could shape the steam coal supply mix and market economics worldwide.

2.3 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 up to 839 mt in 2008 - an increase of 58% compared to the totals from 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[7].

The Pacific market basin saw a large increase not only in domestic production and demand but also in seaward traded volumes (Table 2.1). 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 have included India and especially China, whose import volumes are growing rapidly.

The Atlantic market region is dominated by three large net exporters, Colombia, Russia and South Africa (Table 2.2). The U.S. has been a swing supplier in the Atlantic basin,

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

Table 2.1: Main players in the Pacific basin for 2008 in mt (Source: IEA, 2011a).

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

and mid- to high-cost U.S. mines have been marginal suppliers for Europe in recent years (Kopal, 2007). 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 efforts to phase out of German coal mines by 2018 and the decline 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, 2011a, Ritschel, 2011).

Table 2.2: Main players in the Atlantic basin for 2008 in mt (Source: IEA, 2011a).

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

2.4 The model

The global steam coal market is modelled as a spatial intertemporal equilibrium model. There are three types of model entities: mine owners, port operators and coal consumers. Nodes representing port facilities, mine regions and demand regions are assigned to each actor[8]. 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[9]. The global steam coal market is generally considered to be well integrated[10].

2.4.1 Notation

In this section, the sets, parameters and variables used in the model formulation are described. The time horizon of the model $T = \{2005, 2006, \dots, t, \dots, 2040\}$ includes one-year time periods from 2005 until 2015 and five-year time periods from 2015 to 2040[11]. 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 2.3 and Table 2.4, 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 and Gjelsvik (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 linear trend with slope $\beta_{m,t} \geq 0$ until production reaches almost capacity limit. As soon as the supply level approaches production capacity limits, the marginal costs can increase exponentially depending on parameter $\gamma_{m,t} \leq 0$. The economic intuition behind using this functional form for marginal costs is that prices during periods with higher demand are in reality often set by older mine deposits. Coal mining conditions decline over time as cumulated coal production increases and the cheapest reserves have been exploited. Coal mines may push their production capacity limits within a certain extent by increasing their labor and machinery inputs

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

[9] 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.

[10] Empirical evidence for steam coal market integration is for example given in Li (2008) or 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 may exert market power through volumes or through taxes.

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

Table 2.3: Model parameters.

Parameter	Dimension	Description
$c^{I,M}_{m,t}$	mn. USD_{2009}/mtpa	Investment costs in region m for mine investments
$c^{I,P}_{p,t}$	mn. USD_{2009}/mtpa	Investment costs in region p for port investments
$C_{m,t}$	mn. USD_{2009}/mt	Mine production cost function in region m
$c^{S,M}_{m,t}$	mn. USD_{2009}/mt	Marginal mine production cost function in region m
$c^{T}_{a_{(i,j)},t}$	mn. USD_{2009}/mt	Specific transport costs on arc $a_{(i,j)}$
$Cap^{M}_{m,t}$	mtpa	Existing mine capacity in region m
$Cap^{M,max}_{m,t}$	mtpa	Max. mine capacity investment potential in mine region m
$Cap^{P}_{p,t}$	mtpa	Port capacity in port p
$c^{P}_{p,t}$	mn. USD_{2009}/mt	Specific turnover costs at port p
$Cap^{T}_{a_{(i,j)},t}$	mtpa	Transport capacity between node i and node j
$D_{i,t}$	mt	Steam coal demand at import region i
d_t	-	discount factor

above planned levels or by mining a coal seam that only becomes profitable if market prices rise to certain levels.

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

$$c_{m,t}(S_{m,t}) = \alpha_{m,t} + \beta_{m,t} S_{m,t} + \gamma_{m,t} \ln \left(\frac{Cap^{M}_{m,t} + \sum_{t'=2011}^{t} I^{M}_{m,t'} - S_{m,t}}{Cap^{M}_{m,t} + \sum_{t'=2011}^{t} I^{M}_{m,t'}} \right), \tag{2.1}$$

for $S_{m,t} \in [0, Cap^{M}_{m,t} + \sum_{t'=2011}^{t} I^{M}_{m,t'})$ and $\alpha_{m,t}, \beta_{m,t} \geq 0,\ \gamma_{m,t} \leq 0$.

Table 2.4: Model variables.

Variable	Dimension	Description
$S_{m,t}$	mt	Amount of supply in mine region m
$I^{M}_{m,t}$	mtpa	Mine capacity investment in mine region m
$I^{P}_{p,t}$	mtpa	Port capacity investment at export harbor p
$T_{a_{(i,j)},t}$	mt	Total transport volume on arc $a_{(i,j)}$
$\mu_{n,t}$	mn. USD_{2009}/mt	marginal costs of supply in node n
$\lambda_{m,t}$	mn. USD_{2009}/mt	capacity scarcity rent in mining region m
$\epsilon_{p,t}$	mn. USD_{2009}/mt	capacity scarcity rent for export terminal p

2.4.2 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 within the welfare maximisation problem in spatial markets if demand elasticities are set to zero and require that demand has to be satisfied in every period and region. The resulting equilibrium corresponds to a perfectly competitive market 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 centers. 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:

$$\begin{aligned}\min_{x\in\Omega} O(x) = &\sum_{t\in T} d_t \Bigg[\sum_{m\in M} \left(C_{m,t}(S_{m,t}) + c^{I,M}_{m,t} I^{I,M}_{m,t} \right) \\ &+ \sum_{a_{(i,j)}\in A} c^{T}_{a_{(i,j)},t} T_{a_{(i,j)},t} + \sum_{p\in P} \left(c^{P}_{p,t} \sum_{i\in I} T_{a_{(p,i)},t} + c^{I,P}_{p,t} I^{I,P}_{p,t} \right) \Bigg],\end{aligned} \tag{2.2}$$

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 constrained by a set of model constrains:

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

$$S_{m,t} - \sum_{p\in P} T_{a_{(m,p)},t} = 0 \qquad (\mu_{m,t}) \qquad \forall m, t. \tag{2.3}$$

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

$$\sum_{m\in M} T_{a_{(m,p)},t} - \sum_{i\in I} T_{a_{(p,i)},t} = 0 \qquad (\mu_{p,t}) \qquad \forall p, t. \tag{2.4}$$

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

$$\sum_{p \in P} T_{a_{(p,i)},t} - D_{i,t} = 0 \qquad (\mu_{i,t}) \qquad \forall i, t. \tag{2.5}$$

Mine production is restricted by mine capacity limits. However, endogenous mine investments are possible from 2011 onward:

$$S_{m,t} - \sum_{t'=2011}^{t} I^{M}_{m,t'} - Cap^{M}_{m,t} \leq 0, \qquad (\lambda_{m,t}) \qquad \forall m, t. \tag{2.6}$$

The same holds for port capacities:

$$\sum_{i \in I} T_{a_{(p,i)},t} - \sum_{t'=2011}^{t} I^{P}_{p,t'} - Cap^{P}_{p,t} \leq 0, \qquad (\phi_{p,t}) \qquad \forall p, t. \tag{2.7}$$

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 (2009) so that it is possible to restrict:

$$\sum_{t'=2011}^{t} I^{M}_{m,t'} - Cap^{M,max}_{m,t} \leq 0, \qquad (\epsilon_{m,t}) \qquad \forall m, t. \tag{2.8}$$

The objective function and the restrictions (2.3) to (2.8) form the minimisation 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[12].

2.5 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

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[12] 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 (1995) 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 the appendix. Both approaches yield the same optimal solution.

some publications on steam coal markets available from public institutions like the IEA ((IEA, 2011a) or the EIA (EIA, 2007, 2010a,b), comprehensive information is especially obtained from the published reports of the IEA Clean Coal Center: e.g., Baruya (2007, 2009), Minchener (2004, 2007) and Crocker and Kowalchuk (2008). Furthermore, Ritschel (2011) and Schiffer and Ritschel (2007) are publishing annual reports on the developments in the hard coal markets. Further publications include analyses from employees working for international utilities; for example, Bayer et al. (2009), Rademacher (2008) and Kopal (2007). Industry yearbooks and governmental reports provide useful information as in the case of China (CCII, 2007, CMR, 2010, NBS, 2008). National statistics bureaus and mineral ministries provide high quality information; as for example, ABARES (2011) 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 and Paulus (2010) 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. Eichmüller (2010) derives mining and transportation cost estimates as well as mining capacities for domestic markets in China and the U.S., which are used in the model within this 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 (2011a), Ritschel (2011) and BGR (2008).

2.5.1 Topology

Table 2.5 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 import regions. The term *new mine regions* refers to mine-type nodes that represent still-untapped mining potential in the respecting 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 centers. All together, 287 transport routes have been modelled.

Table 2.5: Model topology.

Mine regions	Export terminals	Demand regions	New mine regions
QLD UG	QLD	North-western Europe	Australia invest
QLD OC	NSW	Mediterranean Europe	South Africa invest
NSW OG	South Africa	Japan	Indonesia invest
NSW 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	U.S. - North Atlantic	China - Xinjiang invest
Russia Kuzbass	China	U.S. - South Atlantic	PRC - Shaanxi invest
Colombia	U.S. east coast	U.S. - SE central	
China - Shaanxi	Venezuela	U.S. - SW central	
China - Shanxi	Vietnam	U.S. - Central	
China - Shangdong		U.S. - NW central	
China - Henan		U.S. - Western	
China - IMAR		Other Asia	
China - other		Brazil	
U.S. - Northern App.		Chile	
U.S. - Southern App.		China - Beijing	
U.S. - Illinois basin		China - Shanghai	
U.S. - Northern PRB		China - Hong Kong	
U.S. - Southern PRB		China - West	
Venezuela		China - North	
Vietnam			

2.5.2 Mining costs

Costs for mining include coal extraction costs, costs for coal processing and washing as well as transportation costs within the coal pits. 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 annual reports of coal companies, expert interviews and literature sources. The available data of mine mouth cash costs and mine capacity is fitted to the marginal cost function described in section 4.3 by ordinary least squares (an overview of marginal mining costs can be found in the appendix in Table A.1). In this way, it is possible to extract 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 to their relative importance in the production process. The relative importance of input factors is derived from a number of sources. Table 2.6 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. For a more detailed description of mining technologies refer to Hustrulid (1982) or Simpson (1999).

Table 2.6: Input factors by relative importance for coal mining production costs in 2005 (Source: Trüby and Paulus, 2010).

in %	Diesel	Explosives	Tyres	Steel products	Electricity	Labor	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

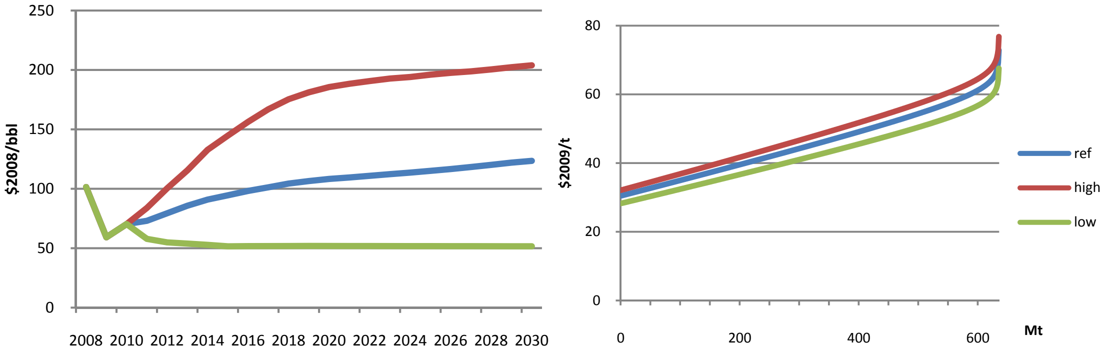

Figure 2.1: Influence of different oil price projections (left) on the marginal mining costs in Shanxi, China in 2030 (right).

Many of the relevant input factor prices for mining, including those for explosives, chemicals, and diesel, are correlated to 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 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 2.1 demonstrates how the oil price projections of the EIA for the 'high', 'reference' and 'low' oil price cases influence marginal mine production costs for Shanxi (PR of China) in the year 2030.

2.5.3 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 2.7 are absolute demand figures for China and the U.S. For the other demand regions, these figures should be interpreted as import demand.

Table 2.7: Demand figures in mt for 2005 and 2006 and demand projections until 2030 (Source: EIA, 2010b).

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
the U.S.	990	978	914	968
People's Republic of China	1761	1932	3127	4190

2.6 Scenario setup

In the scenario analysis, the feedbacks which two different Chinese bulk energy transport strategies have on the coal supply mix in China and the kind of feedbacks that occur 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 centers where an opportunity for foreign 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 centers. 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 mine 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.

2.6.1 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 production 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 2.2). 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 Xinjiang, where coal reserves are plentiful and could still be mined in cost-efficient 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 course of recent years to cope with the rising coal transport demand (APERC, 2008, Sagawa and Koizumi, 2007). While railway transportation tariffs are high, these tariffs already include mark-ups for investment costs for railway expansion projects[13].

2.6.2 Scenario 'coal-by-wire'

In the second scenario, called 'coal-by-wire', it is assumed that, for new mine 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 centers 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 centers 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 (APERC, 2008, Minchener, 2007). China lacks a central energy planning institution necessary for the large-scale efficient realisation of HVDC grid infrastructure. Approval of large infrastructure investment projects is divided among

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[13] Transporting one tonne of coal from Shanxi to Hong Kong costs about 36 USD/t by railway in 2005 (CMR, 2010). The Chinese Ministry of Railways publishes annually 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.

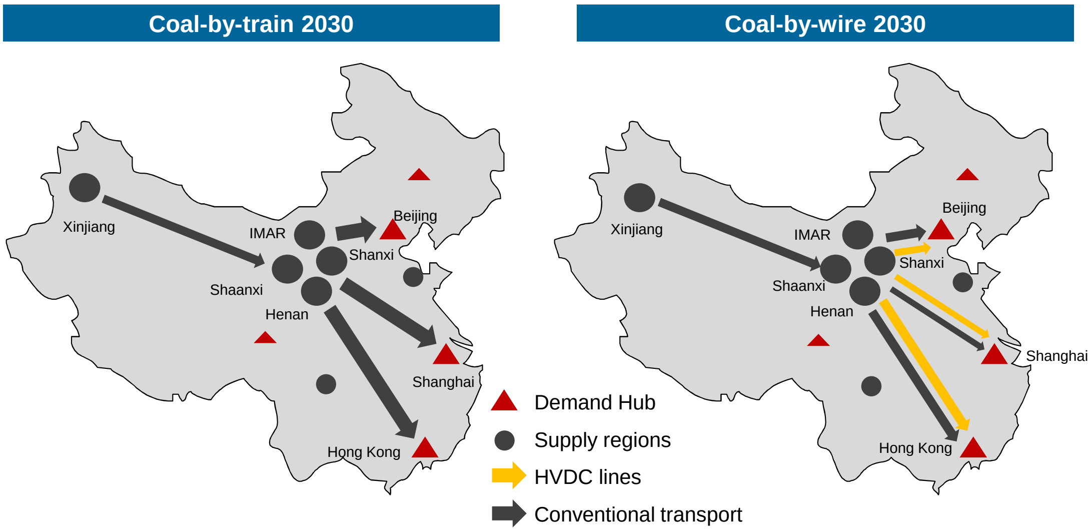

FIGURE 2.2: Topology of the scenario setup for China.

many different departments. The weakness of central Chinese institutions promotes the assertion currently decisions regarding the energy system in China are often made on the grass-roots level, which has so far partly hindered the fast 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 enough 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 burnt, and the generated electricity will be transported with HVDC lines to the demand centers 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 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/I-MAR, and generated electricity is afterward transported via HVDC transmission to the coastal demand centers.

Table 2.8: Domestic steam coal transport costs for new-built mines in both scenarios.

		2005	2020		2030	
in USD_{2009}/t			by-wire	by-train	by-wire	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.

2.6.3 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 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 2.8 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.

2.7 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 the appendix.

Table 2.9: Steam coal production, imports and exports in China.

	2005		2006		2020		2030	
in mt	Ref.[a]	Model	Ref.[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 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[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[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 CCII (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* also comprise 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 centers.

2.7.1 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 2.9 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[14].

In the coal-by-train scenario, the main coal suppliers are the central Chinese provinces Shanxi, Shaanxi and IMAR in 2030. A large portion of the coal production is hauled

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[14] In addition to statistical errors and differences in energy-mass conversions, coal quality is a factor which may let model results deviate 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 may use for generation. Coal specifications on sulfur, 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.

via railway to the coastal demand centers. About 1155 mt of Chinese production is transported to the northern export terminals of Qinhuangdao and shipped via handysize 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 land transports in 2030. The production in the rest of China amounts to approximately 936 mt and is therefore slightly above todays levels.

Imports play a significant role in the coal-by-train scenario, amounting to up to 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 steam coal market. Main importers into China are Australian mines with 151 mt and Indonesian mines 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 greatly 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 into China in the coal-by-train scenario and Indonesian mining costs plus transport charges constitute the marginal costs of supply into 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 has reduced 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 - 22 USD_{2009}/t by 2030. With the reduced transport cost burden, these mines belong to 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. In this scenario, China is even able to export 69 mt.

2.7.2 Long-run marginal costs of steam coal supply

With the different allocation of volumes between both scenarios, the marginal costs of supply also change[15]. As cheaper volumes become available, high-cost suppliers are pushed out of the market and the marginal costs of supply to import regions decline.

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[15] 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

Table 2.10: Evolution of long-run marginal costs of supply for demand regions in Europe, China and Japan.

	2005		2006		2020		2030^b	
in USD_{2009}/t (of coal)	Ref.[a]	Model	Ref.[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
North-Western 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 (2011a) and from EIA (2007). The IEA only publishes an average import price for each country. The reference country for the model region 'North-Western Europe' are the Netherlands, while the reference country for 'Mediterranean Europe' is Italy. The EIA publishes only 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.

Table 2.10 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 of mines or utilisation of so 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 mine capacity which is opened up in the western province of Xinjiang. This mine capacity becomes highly cost competitive 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 USD_{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.

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costs, transport costs, turnover costs. The projected marginal costs for 2020 and 2030 also cover mine and port capacity investments.

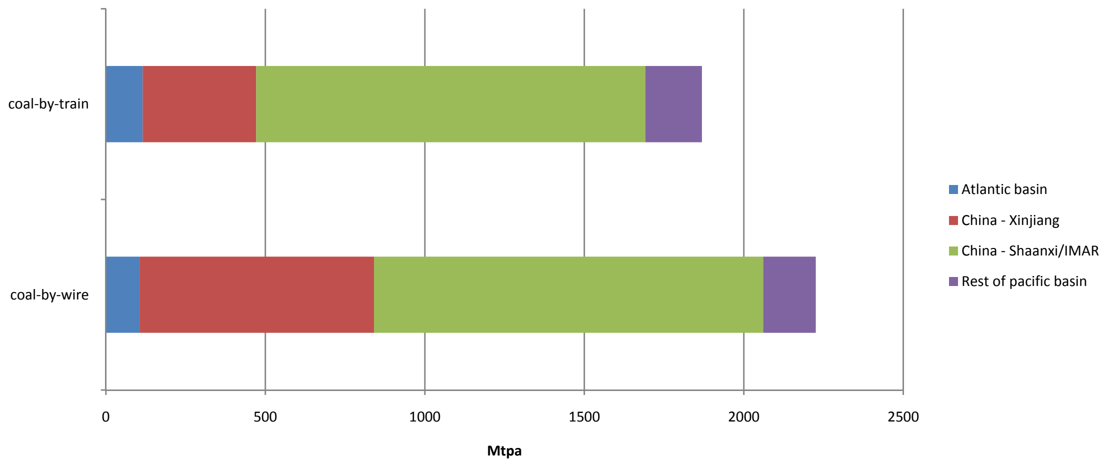

FIGURE 2.3: Cumulated mine investments in mtpa in the global steam coal market until 2030.

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 import 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 - 42 USD_{2009}/t in 2030.

2.7.3 Investment and utilisation of mines

Figure 2.3 shows the cumulated mine investments for both scenarios until 2030. Global mine capacity additions in the coal-by-train scenario amount up to 1927 mtpa and in the coal-by-wire scenario up to 2254 mtpa. The difference in mine investments between both scenarios is largely explained by the higher investments in Xinjiang. Investments into mine capacity in west China are by about 380 mt higher in the coal-by-wire scenario. Mine investments in the rest of the world are approximately 50 mtpa lower in the coal-by-wire scenario. Fewer investments take mainly place in the U.S., Russia and Indonesia.

The difference in mine investments leads to a change in mine utilisation. 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 mine capacity. Existing high-cost mines have a lower production output as the new, cheaper Chinese capacity coming on line partly crowds them out. Table 2.11 shows mine utilisation levels for Chinese

Table 2.11: Utilisation levels of U.S. and Chinese mines.

	2020		2030	
in [%]	coal-by-wire	coal-by-train	coal-by-wire	coal-by-train
U.S. - Northern Appalachia	57	62	69	84
U.S. - Southern Appalachia	64	69	75	89
U.S. - Illinois basin	100	100	100	100
U.S. - Northern PRB	97	97	98	99
U.S. - 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

and US mine 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 belong to the most expensive capacities available. In China, particularly 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.

2.7.4 Welfare effects

Lower worldwide marginal costs in the coal-by-wire scenario lead to welfare effects and changes in the spatial distribution of rents[16] (Figure 2.4). In total, gross welfare effects are positive and amount to 248 billion USD_{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 the countries besides China are dropping by 163 billion USD_{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 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 USD_{2009} cumulated until 2030. The biggest portion

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

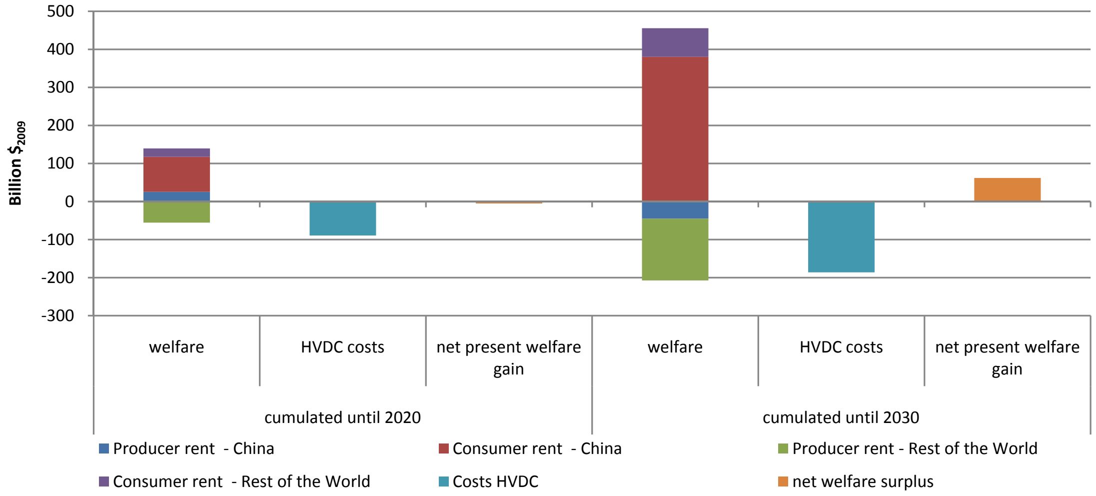

FIGURE 2.4: Cumulated net present welfare and cost effects between both scenarios until 2020 and until 2030 (horizontal axis represents the coal-by-train scenario).

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[17]. 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 USD_{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 until 2030. This means an increase of roughly 40% of the current global steam coal demand which only takes place in China.

On a global scale, the 'coal-by-wire' configuration leads to cumulated net present welfare gains of -5 billion USD_{2009} by 2020 and 62 billion USD_{2009} by 2030. This may seem quite modest compared to the investment costs and welfare changes involved. However, if the welfare analysis just focuses on China, the picture changes; cumulated net welfare surplus including HVDC investments for China amounts to 28 billion USD_{2009} by 2020 and 149 billion USD_{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

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[17] 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 realise 6,800 full load hours on average and 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.

be crowded out, and cost-competitive suppliers in Australia, South Africa and domestic U.S. suppliers could face severely reduced profits as a results of the price pressure induced by new mines in Xinjiang, Shaanxi and IMAR.

2.8 Conclusions

This 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 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 own 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 (U.S.) is exchanged for another (Russia).

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 profit on a global scale of 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 implicates the need for mining companies to strengthen their exploration efforts in order to generate proven reserves which are cheap to mine.

It is suggested that further research investigate in more detail how the steam coal supply mix of the other main 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 mine investment decisions.

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 (IEA, 2011a). Although most of the coal is produced and consumed domestically, international steam coal trade is on the rise[18]. 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 (Ritschel, 2011). Prices decreased with the fall of the financial crisis in the second half of 2008 but remained relatively high throughout 2009 and 2010[19].

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

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[18] 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.

[19] 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.

exporter at the beginning of the last decade has drastically increased imports since 2005.

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[20]. 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), 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

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

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, since that time the steam coal trade market has changed substantially. We follow the approach of Kolstad and Abbey (1984) by using an 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 to 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[21]. Second, we use a different database and generalise the model for multi-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 paper is structured as follows: First, we will briefly outline the current situation on the seaborne steam coal trade market. Section three proceeds with a detailed description of the model and its properties. Then, in section four the supply and demand side data input is described. The scenario design is outlined in section five. Section six presents the model results. Section seven discusses results for 2008, and finally, section eight concludes the 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[22]. The two largest domestic markets are China and the U.S., together comprising more than

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[21] 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 modelled in both analyses. With an increasing marginal cost function, this systematically raises prices compared to ignoring these demand regions.

[22] See Ritschel (2011); includes coking coal.

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 mining industries[23]. 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 U.S., 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[24]. Major importing regions in the Atlantic market are the U.S. 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

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

[24] 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 this paper in a geographical sense to better structure our analysis.

routes. It is assumed that the exporters' objective is to maximise their respective profits. Importers are assumed to act as price takers[25]. The optimisation model is formulated as a mixed complementary problem (MCP) by deriving the Karush-Kuhn-Tucker (KKT) conditions. In equilibrium, the set of prices and quantities simultaneously satisfies all maximisation 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 this paper[26].

Table 3.1: Model regions.

Export regions	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	U.S.	
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[27] 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.

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[25] 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.

[26] 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.

[27] 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.

Individual transport cost functions were calculated for every year based on historical data[28]. Import demand is represented by a linear function of the form:

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

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:

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

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:

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

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

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

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[28] 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.

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:

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

$$\frac{\partial W_i}{\partial q_i} + \gamma_i - \mu_z = \alpha_i \cdot q_i^2 + b_i \cdot q_i + \rho_i + \gamma_i - \mu_z \geq 0 \perp q_i \geq 0 \tag{3.9}$$

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

$$-q_i + C_i \geq 0 \perp \gamma_i \geq 0 \tag{3.11}$$

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 (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).

$$\tau_{z,j} - \alpha_j - 2b_j \cdot x_{z,j} + \mu_z \geq 0 \perp x_{z,j} \geq 0 \tag{3.8a}$$

$$\tau_{z,j} - \alpha_j - b_j \cdot x_{z,j} + \mu_z \geq 0 \perp x_{z,j} \geq 0 \tag{3.8b}$$

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[29].

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[30]. Detailed data on supply chain costs, steam coal demand, and production of major players are available from the IEA Clean Coal Centre[31]. Further publications include analyses from employees working for international utilities and coal industry newsletters[32]. National statistics bureaus and ministries concerned with minerals, energy, and resources provide detailed information[33]. 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

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[29] See Rutherford (1995) or Ferris and Munson (1998) for detailed information on complementary programming in GAMS.

[30] See EIA (2010a,b), IEA (2011a).

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

[32] See e.g. Kopal (2007), Rademacher (2008), Bayer et al. (2009) and Ritschel (2011). The McCloskey Coal Report is regularly reviewed.

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

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 (2011), BGR (2008), and IEA (2011a).

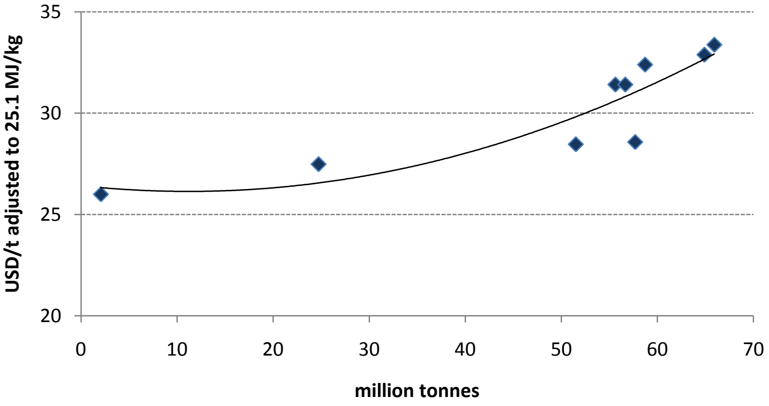

Figure 3.1: Example of FOB costs for Colombia and approximation of marginal cost function for 2006.

These supply curves are complemented by country and technology-specific mining cost structures and are escalated using input price data. These cost structures 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 (2011), 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 U.S. or Australia.

Table 3.2: Input factors and relative importance in coal mining 2006. (Sources: ABS, 2006, Meister, 2008, Paulus and Trüby, 2011).

in %	Diesel fuel & 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

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 extend on labour costs, electricity prices, and locally sourced materials. With the extension of steel products, which are also an important input in deep mining, the increasing prices of fuel and oil derivatives, explosives, and tyres did not raise underground mining costs.

TABLE 3.3: Average FOB costs in USD/t and export capacity adjusted to 25.1 MJ/kg, (Source: Bayer et al., 2009, Kopal, 2007, Rademacher, 2008).

	Average costs			Export capacity		
	2006	2008		2006	2008	
Indonesia	33	44	33%	154	197	28%
Colombia	31	42	34%	59	74	25%
China (Shanxi)	34	44	30%	62	45	-27%
U.S. (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%

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 25 mt 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 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 logarithmic freight cost functions based on distance, which is regressed against a dataset of freight cost observations for 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)[34]. 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[35]. 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.

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[34] Reference quantities are based on Ritschel (2011) and IEA (2011a,c). We used the MCIS steam coal markers for reference price data in the model.

[35] 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.

Table 3.4: Steam coal reference demand in million tonnes adjusted to 25.1 MJ/kg, (Source: IEA, 2011a, Ritschel, 2011).

	Europe	Japan	India	L. America	China	Taiwan	Korea	N. America	S.-E. Asia
2006	187	110	26	9	46	60	62	42	29
2008	184	118	35	16	46	60	72	38	36

Several econometric analyses on short-run steam coal demand elasticities and interfuel 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, timeframe, and methodological approach, all authors find that price elasticity of steam coal demand is inelastic ($|\text{Elasticity}| < 1$).

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

Article	Methodology	Time period	Sector	Region	$\lvert Elasticity \rvert$
Dahl and Ko (1998)	Panel data	1991-1993	Electricity	U.S.	0.16-0.26
Ko (1993)	Time series	1949-1991	Electricity	U.S.	0.25
Kulshreshtha and Parikh (2000)	Time series	1970-1995	Electricity	India	0.34
Söderholm (2001)	Panel data	1984-1994	Electricity	Europe	0.05-0.29
Masih and Masih (1996)	Time series	1970-1992	all sectors	China	0.25
ABARES (1991)	Time series	1978-1988	Electricity	OECD	0.16
Chan and Lee (1997)	Time series	1953-1994	all sectors	China	0.26-0.32
Ko and Dahl (2001)	Panel data	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 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 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[36]. 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

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

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[37]. 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[38]. In this 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[39]. Hence, we model only dedicated export mining capacity[40].

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).

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[37] 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).

[38] 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).

[39] See Ekawan and Duchêne (2006).

[40] 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.

The issue of mining concessions is government controlled and is nowadays only granted to Indonesian companies[41]. 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[42], but the crucial export terminals are controlled by consortia consisting of the major players in the country[43]. 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[44]. 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 market significantly. Chinese authorities have intervened regularly in resource markets and have continuously reduced steam coal export quotas[45]. Russia, the U.S., 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.

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[41] See Baruya (2009).

[42] 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).

[43] 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).

[44] 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)).

[45] 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, Wuyuan and 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).

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[46]. 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.

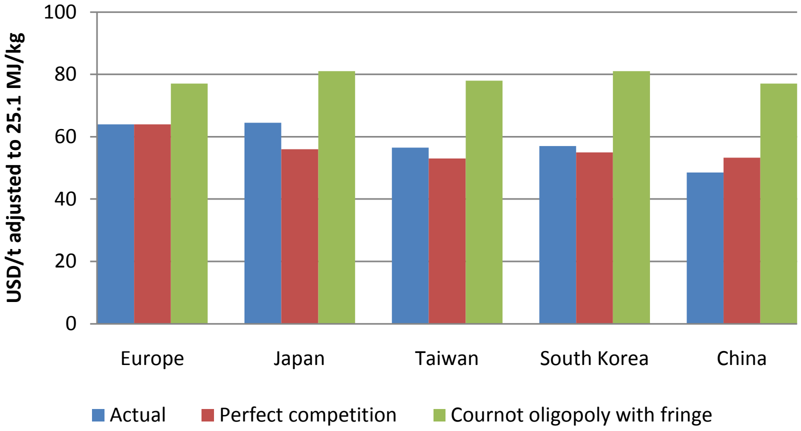

FIGURE 3.2: Comparison of actual and simulated prices in 2006.

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 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[47]. 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[48].

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[46] 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.

[47] 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.

[48] 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

Table 3.6: Comparison of actual and simulated trade flows in mt (energy adjusted).

	SA	RU	VE	VN	IR	CO	PRC	the U.S.	AU	PL	NW
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

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

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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.

Especiallly, 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.

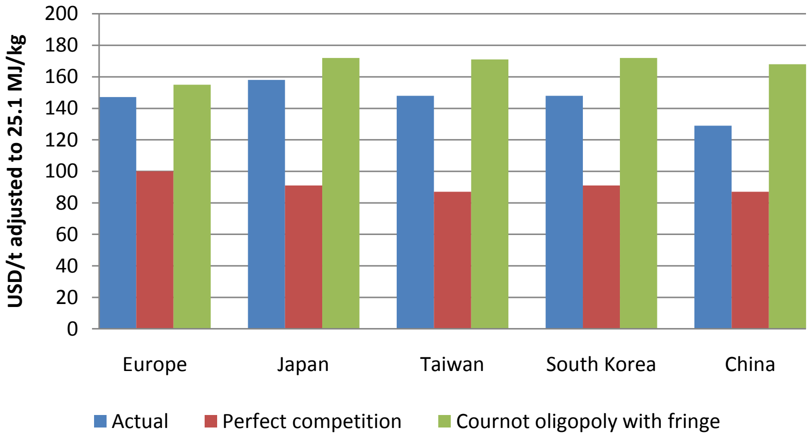

Figure 3.3: Comparison of actual and simulated prices in 2008.

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 mt (energy adjusted).

	SA	RU	VE	VN	IR	CO	PRC	the U.S.	AU	PL	NW
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		

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 possibile reasons that export capacity may have been scarce during 2008[49]. Although such short-run bottlenecks are hard

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[49] The national market in the U.S. 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

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 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.

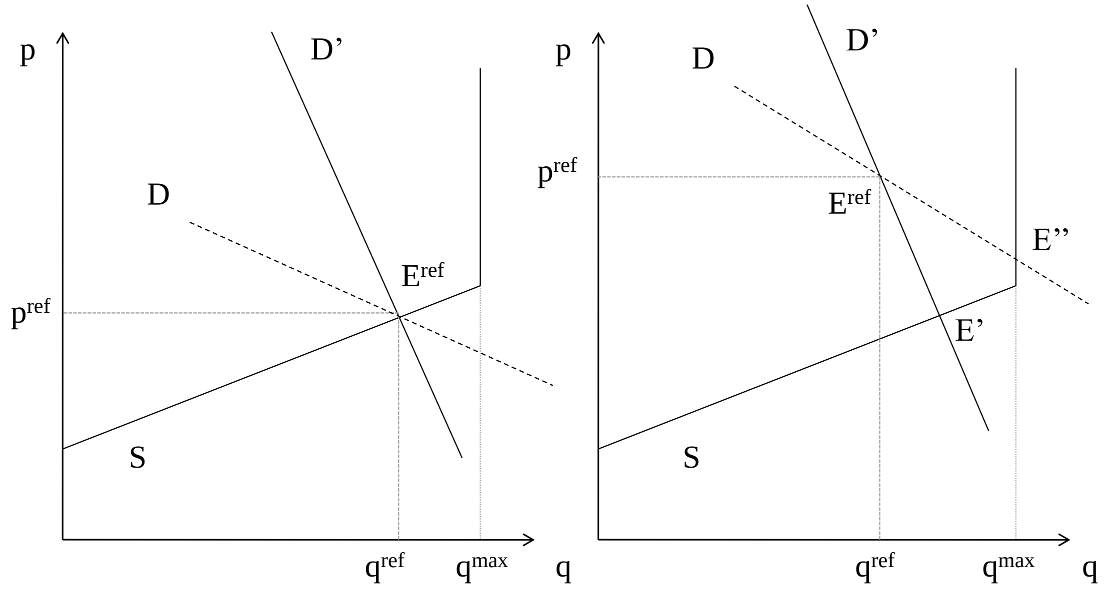

FIGURE 3.4: Comparison of competitive market equilibria under different elastiticity assumptions.

Ritschel (2011) 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.

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 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.

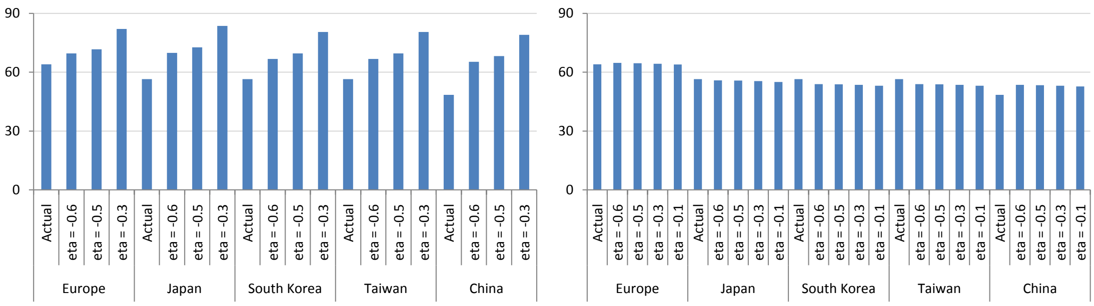

FIGURE 3.5: Prices in USD/t for different elasticity values (eta) in the year 2006 for oligopoly with fringe (left) and perfect competition (right).

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[50].

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[50] Actually, traded quantity (reference quantitiy) 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).

The simulated competitive market size is larger than the historic market volume (reference quantities).

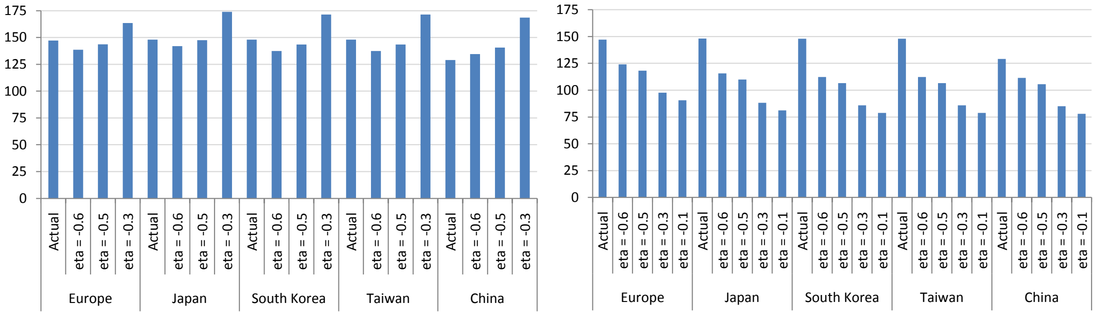

FIGURE 3.6: Prices in USD/t for different elasticity values (eta) in the year 2008 for oligopoly with fringe (left) and perfect competition (right)[a].

[a]Note that 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 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 percent.

	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%

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.

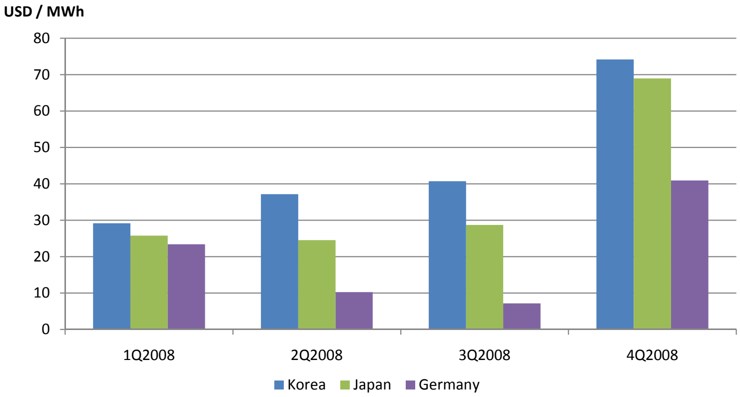

Figure 3.7: Cost advantage of coal vs. natural gas in power generation[a], (Source: EEX, 2011, IEA, 2011a, 2010).

[a] We assume average coal power plant efficiencies of 41% (Japan), 40% (Germany), and 36% (Korea) (IEA, 2010). 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 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[51]. 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 this 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.

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[51] 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.

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 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 concern regarding 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 foundation of OPEC in the 1960s can be viewed as a well-known case for promoting strategic trade- and resource policies, other markets for natural resources have just recently been politicised. A prominent example is the rare earth elements industry in China. Since 2008-2009, the Chinese government made significant efforts to bring this resource sector under tight control through industry consolidation and creation of strategic stocks and, most importantly, by imposing trade restrictions upon exports of rare earth elements. Recent discussions have addressed whether the aim of this policy was indeed the conservation of domestic resources or the preparation of monopoly power exploitation against high technology nations such as Japan and the West (Hurst, 2010, 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 in which production takes place through 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 (e.g., natural gas exporters). Such trade policy instruments can be intended to increase national welfare by influencing the market outcome in a non-competitive manner.

Another commodity market that has raised doubts regarding its competitiveness is the market for internationally traded steam coal (Trüby and Paulus, 2011). For decades, international coal trade has been considered competitive, since production is geographically dispersed and is carried out by a blend of multinational private mining companies, large state-run entities, and various smaller national players (Kolstad and Abbey, 1984). However, recent developments in international steam coal trade have lead to concerns about market structure and conduct. Indeed, several institutional developments support the hypothesis of steam coal market distortion. Firstly, strong economic growth in Asia has lead to increased coal demand and has thus shifted the center of gravity and price setting from the Atlantic to the Pacific market area. Secondly, coal prices soared between 2006 and 2008 and have since remained relatively high. 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[52].

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). Furthermore, Chinese authorities have significantly lowered coal export quotas and introduced export taxes for coal during this period, thus increasing its tight control over exports (NDRC, 2008).

Moreover, Indonesian steam coal production and exports have undergone a rapid expansion in recent years (IEA, 2011a). This development indicates a switch in the Indonesian national resource policy from oil exports to coal exports. Indonesia pulled out of OPEC in early 2009 in the eyes of diminishing oil stocks and production as well as strong domestic oil demand. Therefore, Indonesia may be currently promoting the strategy to become the dominant player in Asian coal markets to offset its declining oil revenues. The implementation of national resource policies in China and Indonesia have led to a structural shift of steam coal supply in the Pacific basin in recent years. This may have given the authorities of either country the potential to exert market power on a national level.

This paper therefore analyses the export patterns of major national players in the world steam coal market to identify whether Indonesian and Chinese resource policies support the hypothesis of strategic market behaviour on a national level. This analysis is broadly

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[52] These developments have severely affected several OECD countries severely 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 up to more than 60%.

related to the empirical literature on strategic trade policy, which has been developed since the seminal theoretical papers of Brander and Spencer (1985) and Eaton and Grossman (1986) and others. A large part of the empirical contributions to this topic focus on international markets for agricultural goods and make use of diverse methods of analysis (see for example Reimer and Stiegert (2006) for an overview). A recent contribution was made by McCorriston and MacLaren (2007), who analysed the effect of state trading enterprises on international trade in an oligopoly setup. Their model calibration for the global wheat market showed that countries are able to influence trade through such enterprises and that these trade distortions yield significant welfare effects. The existing literature on non-competitive market conduct of national players in international steam coal trade so far focuses on maritime trade. Maritime trade is a submarket of the global market and excludes domestic trade. Kolstad and Abbey (1984) were the first to apply 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) analyse a number of major maritime coal trade routes and test whether trade volumes on these routes fit competitive or oligopolistic behaviour during the years 2005 and 2006. Their results suggest that steam coal trade market is better represented by perfect competition in the analysed periods. However, Trüby and Paulus (2011) model seaborne trade using an equilibrium approach and show that competitive models are unable to reproduce the steam coal trade market equilibria in 2008.

We develop a static partial equilibrium model to test our hypothesis of non-competitive market behaviour exercised through strategic trade policy in global steam coal trade. The model allows us to simulate perfect competition as well as non-competitive market structures in which 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. Modeling of spatial equilibria in commodity markets has already been scrutinised since Samuelson (1952) who applied linear optimisation techniques for competitive market structures. 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).

Using our model, we test different hypotheses on market conduct and validate model results for the year 2008. In contrast to the majority of previous papers using equilibrium programming techniques, we validate our results applying a series of non-parametric tests such as the Wilcoxon-Sign-Rank test, Spearman's rank correlation coefficient test and the Theil inequality coefficient. Based on these statistics, our main finding is that the perfect competition hypothesis can be clearly rejected while a market structure setup with China and Indonesia acting as non-cooperative Cournot players best fits observed trade flows and prices in 2008. Official Chinese steam coal export quotas in 2008 were consistent with simulated Chinese export volumes under a Cournot strategy. Additionally, diversification of simulated Chinese exports streams are close to Chinese real-world export patterns in this case.

Thus, our paper extends the existing literature in two important ways: First, we account for interdependencies and feedback 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 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 (IEA, 2011a). The two largest domestic markets are China and the U.S. 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[53]. Major importing regions in the Atlantic market are the U.S. and Europe (including neighboring Mediterranean countries) with the United Kingdom and Germany at the top. Traditionally these importing regions are primarily supplied by South Africa, Colombia and Russia.

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

The Pacific market has grown more dynamically in recent years. High quantities are imported by Japan, South Korea, and Taiwan - all three of them having virtually no indigenous coal production, and therefore they rely heavily on imports. However, most of the growth has come from emerging import regions like India, Southeast 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.

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 comprise 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 primarily are China, the U.S., 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 between dedicated export mines with domestic markets and domestic mines with export markets is most times 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 coal to domestic power plants. Conversely, mines serving the domestic markets are often located deeper inland[54] 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 of participants' actual potential to exercise market power. Market power potential may exist in the steam coal market in the form of single large coal-producing and -exporting countries behaving in a non-competitive manner. This holds especially true for China and Indonesia.

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[54] 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).

China has increasingly made use of policy instruments, i.e. quotas and/or taxation, to tightly control participation of Chinese firms in the international trade market in recent years[55]. Firstly, political regulations require domestic mining companies to apply for special licenses that allow for a defined export volume. Quotas on steam coal are set and allocated by Chinese institutions on a yearly basis; nevertheless, they may be subject to readjustments in case of political or economical requirements; e.g., the total export volume restriction for steam coal in 2007 was 70 mt and has been reduced to 47.7 mt in 2008 (NDRC, 2007, 2008). Secondly, the Chinese government levies export taxes on steam coal. In 2008 export taxes have been increased to 10% compared to no export tariff for steam coal in 2007 (TRCSC, 2008). These taxes significantly increased the 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 nationwide level are less obvious in Indonesia, there exists a mine ownership structure that is quite special: mining rights have been awarded mostly to international mining companies in the early eighties. However, foreign investors were obliged to offer at least 51 percent of shares to Indonesian companies or the government after 10 years of mine production (Baruya, 2009). Mining rights awarded in the 1990s 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[56] or by the government. Thus, Indonesian policy makers have significant indirect influence on coal export volumes of a majority of Indonesia's coal mining sector. An additional influence 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 practically not capacity constrained, an element that would have allowed Indonesia to export higher volumes than it actually did in 2008. One possible explanation could be that Indonesia actively pursued limits on 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 so far untapped high quality coal fields such

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

[56] One example is PT BUMI Resources which owns the mining companies PT Arutmin and PT Kaltim Prima Coal which together accounted for 54 million tonnes or 32% of Indonesian steam coal exports in 2007.

as those in Botswana, Zimbabwe and Madagascar. Secondly, export capacity expansion usually requires coordination of infrastructure and mining capacity upgrading with different stakeholders being involved. This process can be very slowly 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.

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[57]. In the following, we consider that a strategic national player is an entity that maximises welfare for a given commodity in its domestic market plus its producer rent from sales to the export market less costs.

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.

Intuitively, domestic supply will enter the export market if marginal cost (including the cost disadvantage of domestic production) equals marginal export revenues. If we consider that the national player acts competitively, the marginal export revenue is equal to export market prices. In this case, a setup that takes into account only the trade market will be rendered inconsistent if export prices rise just high enough. If the national player pursues a non-competitive strategy (e.g., à la Cournot), the same holds true. However, export market prices have to be higher, as in this case the national player will account for the price reduction inferred by supplying additional volumes to the export market. If we look at real coal prices in the export market and thus marginal

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[57] 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 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. where most probably not constrained by transport capacity.

revenues, it can be observed that they were particularly high in 2008 (IEA, 2011a) which makes an interaction between 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 against a competitive fringe of other producers.

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

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

4.3 The model

In this section, we develop the model and describe the data we used. We will also outline our market structure scenarios and depict statistical methods we will use to compare model results with actual data. The model is structured to allow us to find the spatial equilibrium of prices and trade flows between a given set of players given assumptions about their market conduct and objective functions. We model three types of players: national producers, which maximise their producer rents from sales to the export market in a Cournot fashion and at the same time maximise the overall welfare in their domestic coal markets (strategic players); producers that 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 that act as price takers. All producers maximise profits subject to a number of capacity constraints and energy balance equations[58].

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

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[58] We model energy flows that account 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). For the sake of simplicity we suppress the energy-mass parameters in the model formulation.

games can be mapped by a term that is a producer's conjecture about the response of other producers to a change in their production volume[59]. This term can be inserted in the producers 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.

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 through transport arcs $(i, j) \in A \subset N \times N$. Sets, parameters and variables of the model are found in Table 4.1.

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 for production, shipping and turnover. The pay-off function $PO_p\,(z_p)\ :\ \mathbb{R}^{|M_p|+|A|+|D|} \mapsto \mathbb{R}$ and the corresponding decision vector z_p can then be written as:

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[59] 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 yield the same equilibrium (see e.g. Kolstad and Abbey, 1984).

Table 4.1: Model sets, parameters and variables.

Sets	
$n \in N$	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
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
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 volume from player p from mining region m to demand region d
λ_n^p	Dual variable associated with the energy balance constraint in node n
μ_m^p	Dual variable associated with the mine capacity constraint in region m
ϵ_e^p	Dual variable associated with the export capacity constraint in port e
$\phi_{(n,n')}$	Dual variable associated with the capacity constraint on arc $a_{n,n'}$

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

with $X_d^- = \sum_{p' \in P^-} x_d^{p'}$. PO_p is 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):

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

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

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

Our model incorporates a complex network topology that 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 enables us to map trade flows from mines to demand regions along several intermediary nodes.

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

$$s_m^p + \sum_{(n,m) \in A} q_{(n,m)}^p = \sum_{(m,n) \in A} q_{(m,n)}^p \qquad (\lambda_m^p) \qquad \forall\, m \in M_p, \tag{4.5}$$

for export regions $e \in E_p$:

$$\sum_{(n,e) \in A} q_{(n,e)}^p = \sum_{(e,n) \in A} q_{(e,n)}^p \qquad (\lambda_e^p) \qquad \forall\, e \in E_p, \tag{4.6}$$

and for demand regions $d \in D$:

$$\sum_{(n,d) \in A} q_{(n,d)}^p = x_d^p + \sum_{(e,n) \in A} q_{(e,n)}^p \qquad (\lambda_d^p) \qquad \forall\, d \in D. \tag{4.7}$$

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 and all depicted 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 from $\mathcal{L}$. The first order partial derivative w.r.t. export volumes x_d^p between player $p \in P$ and $d \in D^-$ is given by

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

The first term is the price in node d and 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_d^p 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 $x_d^p \geq 0$, 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 by withholding volumes. His sales decision for d also depends on his perception on how sales of competitors for d change, given a change in his sales:

$$\frac{\partial v_d}{\partial x_d^p} + \frac{\partial v_d}{\partial X_d^-}\frac{\partial X_d^-}{\partial x_d^p} = \frac{\partial v_d}{\partial x_d^p}(1 + r^{p \to d}). \tag{4.9}$$

$\frac{\partial v_d}{\partial x_d^p} = r^{p \to d}$ is the aggregate conjecture[60] 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.

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.

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

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 and Gjelsvik (1995). In their paper the authors present a production cost function, for which the marginal supply cost curve has an intercept $\alpha_m \geq 0$ and 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 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 strictly convex and continuously differentiable and 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 $(n, n') \in A$. For transport connections going out from mining regions $m \in M$ and from demand regions $d \in D$ price efficiency occurs when marginal costs of supply λ_n^p and $\lambda_{n'}^p$ only differ by transport costs and a possible markup for scarcity rents in the case of congested transport capacity $\phi_{(n,n')}$ if $q_{(n,n')}^p \geq 0$.

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

similar conditions hold for transport connections going out from export terminals but include an additional scarcity markup 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 to:

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

If we bundle the equations (4.15) with the first order conditions (4.17), (4.11), (4.13), (4.14) and capacity constrains (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

Our assumptions regarding reference volumes, and for price elasticities of coal demand in Europe are explained in detail in Trüby and Paulus (2011)[61]. Demand elasticities for other regions are based on a broad literature review of econometric analyses on

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[61] 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.

inter-fuel substitution. While methodological approaches and the age of the reviewed articles differ, all authors agree that the price elasticity of steam coal demand is inelastic $\mid \sigma \mid < 1$. In this paper, we assume a price elasticity of steam coal demand of -0.3 for the other world regions beside Europe.

Information on costs and capacities in the steam coal market is only available from a multitude of heterogeneous sources. We use an extensive steam coal market database in this analysis that has already been presented and used in one of our former analyses (Paulus and Trüby, 2011)[62].

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 4.2). Note that our model includes the two largest domestic markets, China and the US, which together accounted for 65% of global hard coal production and 66% of global consumption. Other major domestic markets are Russia and India which have also been taken into account.

TABLE 4.2: 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	Asia, other	1
Poland	3		

[a] Bold faced entries are countries with large domestic steam coal markets that have been explicitly modelled.

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[62] Relevant publications on steam coal markets are available from public institutions like the IEA (2011a) or the EIA (2007, 2010a,b). Comprehensive information is especially obtained from the published reports of the IEA Clean Coal Center, e.g.: Baruya (2007, 2009), Minchener (2004, 2007) and Crocker and Kowalchuk (2008). Furthermore, Ritschel (2011) and Schiffer and Ritschel (2007) depict recent developments in the hard coal markets. Further publications include analyses from employees working for international utilities as for example Bayer et al. (2009) and Kopal (2007). Industry yearbooks provide useful information as it is the case for China (CCII, 2007, NBS, 2008). National statistics bureaus and mineral ministries provide high quality information as for example ABARES (2011) 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 (2011a), Ritschel (2011) and BGR (2008). For Australia, ABS (2006) delivers detailed information, Baruya (2007) compares different mining input factor structures on the global scale.

4.3.3 Market structure scenarios

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

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 in order to assess how unconstrained Chinese export patterns would have looked like 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 may 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 besides a competitive fringe of other market players. The Chinese export quota is modelled as a fixed export restriction for the Chinese player who behaves as a price taker. This scenario lets us test for the non-competitive behaviour of Indonesia.

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

4.3.4 Model validation using statistical tests

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 non-parametric tests to validate our results: the Wilcoxon-Rank-Sign test and Spearman's rank correlation coefficient test.

The Wilcoxon-Sign-Rank test evaluates the signed-rank correlation between two sets on the basis of a paired sample (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 modelled 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, that is also distribution-free is Spearman's rank correlation coefficient test. Similar to Kolstad and Abbey (1984) 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, which 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 following regression equation:

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

If our model would perfectly simulate each trade flow share, then $\beta = 1$ and $\alpha = 0$. 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 is suited 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 an 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 4.3: Comparison of statistics of actual and modelled trade flows in 2008.

Test statistics[a]	Market structure			
	PC w/o export quota	*PC w. export quota*	*Indonesia monopoly w. export quota*	*China - Indonesia duopoly*
$\rho_{Spearman}$	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 - Trade [%]	23.5	16.9	11.6	**7.9**
RMSPE - Prices[%]	21.7	18.7	4.0	**3.6**
Results on market size in mt				
Error Chinese exports vs. Quota[b]	165%	-	-	6%
Total trade volume (actual = 608)	732	659	645	**628**

[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 $\mid z_{Wilcoxon} \mid$=1.650.

**Significant on the 95% level. Critical values: $\rho_{Spearman}$=0.253 and $\mid z_{Wilcoxon} \mid$=1.960.

***Significant to the 99% level. Critical values: $\rho_{Spearman}$=0.329 and $\mid z_{Wilcoxon} \mid$=2.576.

Critical values are based on Zar (1972) and McCornack (1965).

[b] The Chinese export quota has been set as an exogenous constraint for the scenarios *PC with export quota* and *Indonesia monopoly with export quota*.

4.4 Results

Table 4.3 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). Both non-competitive scenarios cannot be rejected at any typical level of confidence. 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, both non-competitive scenarios cannot 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. Above that, 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 C*hina - 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 being only 2%.

In our model, the amount of international seaborne trade is not predefined as in previous literature. Seaborne trade in the model thus results from the interaction between exporters and importers taking into account that domestic supply may also enter the export market, if demand is sufficiently high. We therefore compare how well the model results for the total trade market volume fit the actual figures. In the *perfect competition without export quota* scenario, the simulated trade market volume is 20% larger than the actual market size in 2008. Modelling this yields to Indonesia and especially China significantly increasing their exports to cover the high international demand in the year 2008. This leads to a drastic overestimation 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 overall trade market volume estimate. The *China - Indonesia duopoly* setting sees the best market volume fit with the estimated trade 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. One interesting spillover is that, under the Cournot assumption, simulated Chinese exports almost meet the export quota. This means that the Chinese export policy was consistent with a Cournot-Nash strategy[63] in 2008. Additionally, in the *China - Indonesia duopoly* scenario Chinese exports are rather similarly diversified as in reality, with Japan, South Korea and Taiwan being the main destinations of Chinese coal exports[64].

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, in which Indonesia's absolute exports are more than 30 million tonnes 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

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[63] Of course this does not necessarily mean that China is a strategic player.

[64] 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 e.g. Brander (1981) and Brander and Krugman (1983)

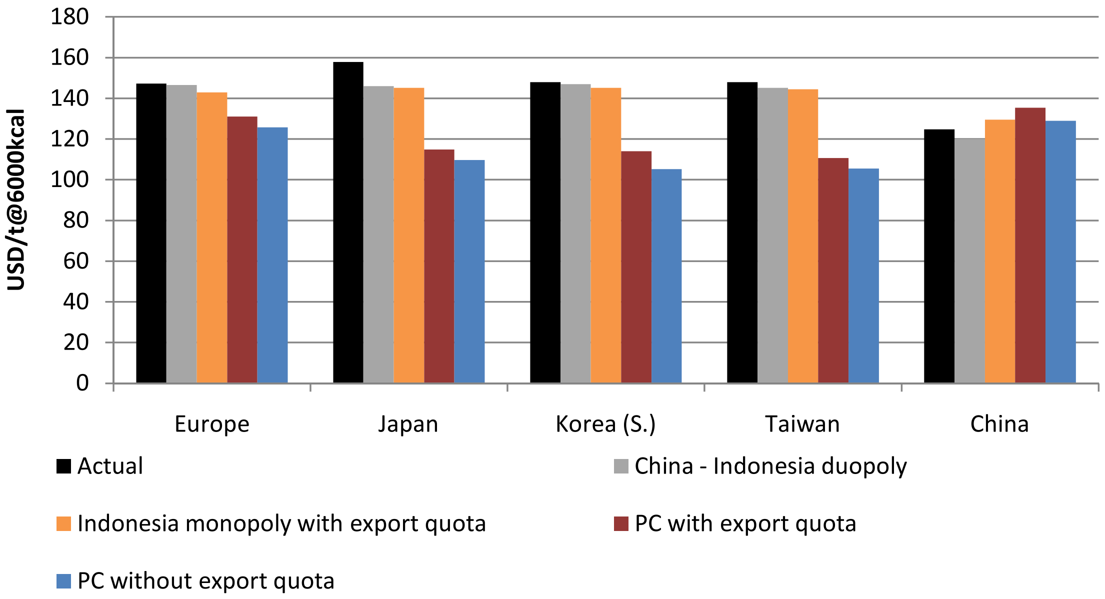

FIGURE 4.1: Comparison of actual and simulated prices for important import regions.

Indonesia monopoly with export quota scenario in all statistics except the bias proportion. However, both non-competitive scenarios cannot be rejected as predictors of actual market outcome.

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

Again, simulated model prices for both non-competitive scenarios fit the observed values better than prices from the perfect competition scenarios. 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 Chinese domestic demand regions and Asian import regions. This protects Chinese domestic demand regions and reduces coal consumer prices. Simulated Japanese import prices may not be completely explained even in the *China-Indonesia duopoly* setup[65]. Besides these deviations, both non-competitive

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[65] 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 may use for generation.

scenarios deliver the most accurate reproduction of actual import prices.

Considering the actual and simulated trade flow matrices, the perfect competition setups features structure of supply that is less diversified than the non-competitive scenarios (see Table C.1 in the Appendix).

4.4.1 Welfare effects

Our results also allow conclusions on global welfare effects. In economic theory, perfect competition (c.p.) leads to the highest overall welfare compared to a scenario with non-competitive market behaviour. The reference for welfare effects is therefore the *perfect competition without Chinese export quota* scenario, presented by the baseline in Figure 4.2.

In the *perfect competition with Chinese export quota* scenario, China accrues less welfare due to its export restriction. Indonesian rents increase to a certain extend due to slightly higher world market prices.

In the *Indonesia monopoly with Chinese export quota* scenario, Indonesian rents increase by around 3 billion USD as the withholdings of Indonesian supply on top of the Chinese export quota significantly increases consumer prices. In this scenario, Chinese welfare effects are close to zero, as positive revenue effects that are due to higher Asian consumer prices and negative effects due to the export quota compensate each other. 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 of 1.4 billion USD while oligopolistic rents of Indonesia decrease slightly. This is due to China's capture of market shares from Indonesia in higher priced regions, like Japan. Chinese rents increase as exports are distributed with regard to export rent maximisation targets taking into account the marginal export revenue generated in each importing country. This leads to a broader (and more realistic) diversification of Chinese export flows among Asian importing countries compared to the scenarios in which China acts as a competitive player. Consumer prices for steam coal in China are slightly lower compared to the Indonesia monopoly scenario, which positively affects Chinese consumer rents.

Coal specifications on sulfur, 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.

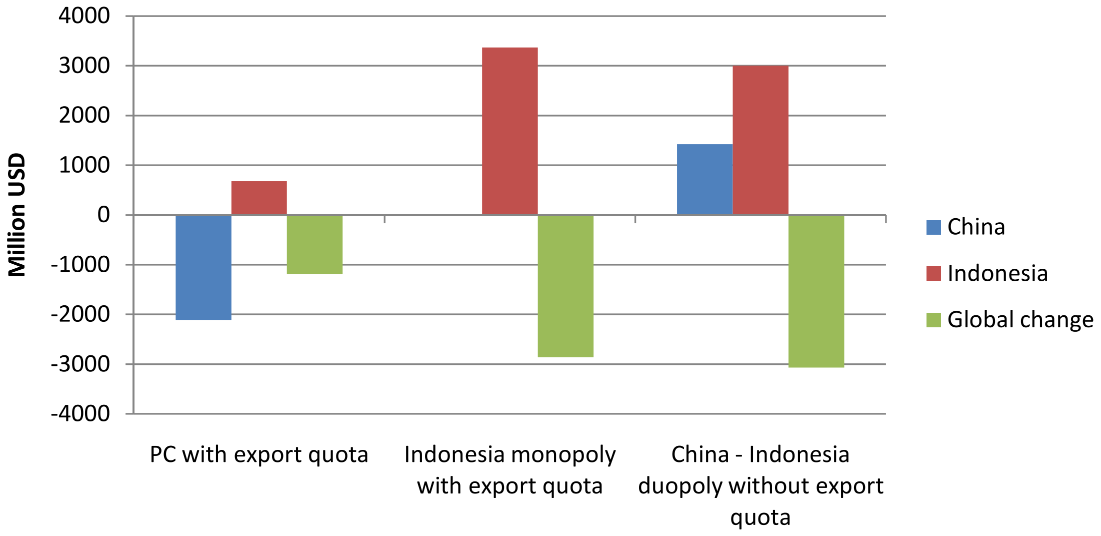

Figure 4.2: Welfare effects in the investigated scenarios (horizontal lines represents the perfect competition scenario without export quota).

Summarising our findings, we conclude that hypothesis H1 (perfect competition) can be clearly rejected based on the employed statistics (see Table 4.3). Prices and trade flow patterns cannot explain the real market outcome.

We find that both non-competitive scenarios cannot be rejected as predictors of actual trade. However, the *China - Indonesia duopoly* outperforms the *Indonesia monopoly with Chinese export quota* scenario in all major statistics. Interestingly, the Cournot-Nash strategy for China reproduces almost exactly the Chinese export quota while Chinese export diversification is clearly closer to observed patterns. The duopoly scenario also shows the highest welfare accruement for China. In the background of the general proactive national energy resource security policy in China, we interpret this as support for H3.

4.5 Conclusions

Due to the increasing demand for natural resources in recent years, several resource-rich nations have reassessed and adjusted their national resource policies. They have applied different instruments of trade policy, such as export quotas and taxes. However, it may not always be clear if these 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 the non-competitive market conduct of China and Indonesia. Both countries have implemented or significantly realigned their coal export strategies in recent years.

For this purpose, we developed a partial equilibrium model, which allowed us to model individual nations as strategic players, maximising welfare in their domestic market 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 validate our modelling results. By that, we find that we cannot reject two non-competitive market setups as predictors of the actual steam coal market in 2008. Additional test statistics indicate that the China-Indonesia duopoly scenario is the better predictor than the Indonesia monopoly scenario. Another important result is that Chinese export quotas are consistent with simulated Chinese export volumes under a Cournot-Nash strategy and that Chinese export patterns are realistically diversified in this setup. These results extend former works that did not reject the competitive market structure assumption but whose analyses were limited to the export submarket. Of course, one could also argue that there are potentially other non-competitive market structure setups that may also be suited to explain trade in 2008. However, in case such other setups exist, the challenge would be to find evidence for their real-world backing. Additionally, our empirical tests support the hypothesis that actual market conduct can be explained by our models.

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 in global commodity markets. Compared to perfect competition, export market prices have to be higher in the case of strategic behaviour to redirect domestic volumes to the export market. Our analysis shows that China has the potential to act as a buffer against global coal demand shocks if it acts competitively. However, we find that we can reject the assumption of perfect competition and that China may pursue a trade policy of withholding domestic capacity from the global market, driving up international coal prices and avoiding domestic price increases.

These results 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 believed by most market participants if emerging Asian nations increasingly pursue their national resource export strategies. This could make it necessary to conduct a reevaluation of the future role of coal in energy consumption of such countries.

Our findings also have implications on a more general level for other natural resources. Markets that have been ravaged by high export prices and where national export quotas or tariffs can be observed, little interaction between domestic and export trade may not always be due to physical market frictions. In such cases, it may prove useful to analyse more closely whether export policies of individual players pursue maximisation of national rent inflow or not.

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

How are investment decisions in the steam coal market affected by demand uncertainty and buyer-side market power?

5.1 Introduction

The optimal sizing and timing of investments in the light of an uncertain market environment is one of the main challenges for capital intensive industries. A typical example is natural resource markets which can require large lump-sum investments for accessing and exploiting resource deposits.

Uncertainty in natural resource markets may be induced by human behaviour (e.g., economic activity or politics) or by natural effects (e.g., weather, floods). While both types of uncertainty are important, major mid-term uncertainty induced by human economic activity for many natural resource markets in recent years has been the speed of Asian demand growth, especially in China. According to the IMF (2011), Chinese economic growth in the first decade of the millennium was 10.2% per year on average. The resulting demand boom regarding all kinds of natural resources to build up Chinese infrastructure and industry incentivised investments into new rigs, mines and refineries on a global scale. However, it is unclear how long the Chinese economy can sustain this kind of growth rates. Investors face the challenge of correctly assessing when Chinese resource demand will flatten out in order not to built up excess capacity.

A rather representative example for a global resource market strongly influenced by Chinese economic growth and resource policies is the global steam coal market. Since 2008, China has made a market shacking shift from one of the largest steam coal exporters to the second-largest net importer of steam coal. However, it remains unclear how imports will develop in the next years. This has created a risky environment for coal mining investors which have to spend large sums upfront for mining equipment and transportation infrastructure in order to set up new capacity (IEA, 2011b).

Furthermore, coal trade control regimes have recently been set up by the Chinese government which further complicates the situation for international investors; coal shipments to China face import duties and export quotas which can be reassessed on an annual basis. It remains to be seen to what extent the Chinese government applies such instrument to influence trade in a strategic way, but doubts about competitive market conduct already exist (Paulus et al., 2011, Trüby and Paulus, 2011).

The main contribution from this paper is an analysis of the projected impact of Chinese market power in the future: We analyse how the interaction between uncertain Chinese coal demand evolution and the opportunity of China to act strategically in the international market affects decisions to invest in mines or infrastructure.

Literature on investments under uncertainty and market power in other resource and commodity markets has a history dating back more than two decades. Haurie et al. (1987) proposed a stochastic dynamic model with players acting in a Cournot manner to simulate contractual agreements in the European gas sector. Murphy et al. (1982) investigated power plant investments under load uncertainty. More recent works focus on investigating how gas industry infrastructure investments are affected by uncertainty and supply-side market power (Egging, 2010, Gabriel and Zhuang, 2006, Zhuang and Gabriel, 2008). Literature on demand side market power has been scarce thus far. One example of such a work is that of Kolstad and Burris (1986) who analyse demand-side market power in agricultural markets. However, their model did not account for investment decisions under uncertainty.

Existing work on steam coal market economics has so far included the analysis of policy scenarios of different transport infrastructure investments regimes (Paulus and Trüby, 2011) and the analysis of interactions between climate policies and coal demand (Haftendorn et al., 2011). Another research venue has been potential supply-side market power. Kolstad and Abbey (1984) analysed strategic behaviour in seaborne steam coal trade on the demand and the supply side. However, since then, the steam coal trade market has changed substantially and several recent papers come to varying conclusions. Haftendorn and Holz (2010) reject the hypothesis of non-competitive market behaviour in coal trade in 2005 and 2006, while Trüby and Paulus (2011) raise doubts about competitive market conduct in 2008 and outline that market structure might have changed due to the growing importance of several major Asian players, most importantly China. Paulus et al. (2011) find that accounting for the interaction between the international market and the domestic market implies that Chinese export policies are consistent with a Cournot-Nash strategy. However, so far no article has focused on how demand side market power and uncertain demand influence investments into coal production capacity.

For our analysis, we model the investment decision problem as a multistage spatial stochastic equilibrium model with recourse. The stochastic perturbation is mapped in extensive form, meaning that possible demand evolutions are represented by a scenario tree and realisation probabilities. The model allows for simulation of competitive behaviour of actors as well as non-competitive market behaviour á la Cournot on the demand as well as on the supply side. We especially account for risk-averse investment behaviour by using stochastic discount factors to generate the deterministic equivalent of uncertain payoffs. The model is designed as a stochastic mixed complementary programme (sMCP) by deriving the first-order optimality conditions of the associated stochastic optimisation problem. Haurie et al. (1987, 1990) found that the information structure of players in such games, which they called *S-adapted Open-Loop*, lies between the adaptive closed-loop and the nonadaptive open-loop information structure and developed conditions for existence and uniqueness of the equilibrium concept (Haurie and Moresino, 2002).

Using an established coal market database described in Paulus and Trüby (2011), we simulate how coal mining investment decisions are affected by uncertain Chinese coal demand evolutions until 2020. We test two setups: in one, we extract the effect of uncertain Chinese demand on international mine investments. All players behave as price takers. In the other setup, we analyse the impact of Chinese market power on the demand uncertainty effect from setup one. Here, China behave as a monopolist/monopsonist regarding exports and imports in addition to the competitive fringe of other players. For both setups we compute the Value of Perfect Information[66] which can be interpreted as the loss in rent for each modelled player due to uncertainty. We find that accounting for Chinese demand uncertainty yields significant costs for investors of 18% of their rents compared to a perfect foresight baseline. Investors reallocate their investments spatially and temporally to hedge themselves against risky demand outcomes. If we account for Chinese market power, China maximises its wellfare by withholding coal imports from the international market to a certain extent. Lower Chinese coal imports make international coal sector investments decrease. However, the Value of Perfect Information is lower for investors in this case.

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[66] Which we sometimes will refer to as 'Costs of Uncertainty'.

The remainder of this paper is structured as follows: In section 5.2 we describe China's current energy policy and potential impacts on coal markets. Section 5.3 describes analytical results, the methodology and the model in detail, while 5.4 outlines the computational application. Section 5.5 shows and discusses the simulation results. Section 5.6 concludes.

5.2 China's energy policy and its potential impact on global coal markets

For decades, international coal trade has been growing at a moderate pace, involving a blend of multinational private mining companies, large state-run entities, and various smaller national players. China has a dominant role in the global coal market; during the last decade, the domestic Chinese steam coal market increased to 2,800 mt in 2010, which was five times more than the total global seaborne trade of 600 mt. Additionally, China has switched from a net exporter of 21 mt in 2008 to a net importer of 80 mt in 2010. This means that variations in domestic coal supply and demand which could be considered as 'noise' compared to the overall Chinese market size potentially amplify and feed back by an order of magnitude to international steam coal markets.

Higher uncertainty with regard to future Chinese coal imports and prices increases the risk for new coal market investments. A significant decrease in profitability could lead international mining companies to decide to allocate investments in other, less uncertain resource markets. Also, if investments are lower than expected, prices could increase and bottlenecks could arise in the global coal supply chain which would also affect energy policies in countries mainly depending on coal imports like many OECD economies. This analysis therefore tries to determine the following in the first step:

- To what extent are investments of international coal market investors affected by Chinese demand uncertainty?
- How large are the profit losses for international producers due to Chinese demand uncertainty?

In addition to the uncertain future Chinese coal import demand, increasingly tighter Chinese coal trade controls represent a second layer of complexity for investors. Such trade controls might be used by the Chinese state to exert market power (Paulus et al., 2011). China has increasingly made use of policy instruments (i.e., quotas and/or taxation) in recent years to tightly control coal exports and imports. As currently one of the largest coal importers, China has significant potential to exert market power through its import taxes. Profitability of investments into new mines may be negatively affected through import taxes, as China may be able to skim producer surplus. It is crucial for international mining investors to know how the potential skimming would affect their profitability and thus their investment plans. This leads us to another question within our analysis:

- To what extent will the exertion of Chinese market power affect investments given that demand is uncertain?

Furthermore, it is not intuitively clear if rent reductions of investors due to uncertainty are higher or lower in a noncompetitive case compared to a competitive case, but this is an important fact for investors to know. If, for example, Chinese import controls would decrease costs of uncertainty, Chinese domestic coal demand fluctuations and energy policies might not have such a profound impact on coal markets as in a competitive market. If investors assume that China is exerting or will exert its market power, analysing and forecasting Chinese trade controls patterns might be more important for international investors than analysing the domestic Chinese coal market. Our last question is therefore thus:

- How will the exertion of Chinese market power affect costs of uncertainty of international producers?

5.3 Methodology and model

In this section, we describe the general layout of our empirical model and the relevant players. Finally, we formulate the model in terms of a simple multi-stage stochastic programme and derive the necessary first order conditions.

5.3.1 Layout of the model

The empirical model is structured to find the spatial and temporal equilibrium of prices, trade flows and investments between players given assumptions about their market conduct and objective functions. The model accounts for the following three different types of players:

1. Investors I maximise their profits given uncertain future demand in a competitive manner. Investments into additional capacity stock have to be decided prior to

demand realisation. Production levels are recourse variables which are decided on during the period in which the demand level is revealed. Investors are risk averse in the sense that they price their systematic risk (see Section 5.3.2).

2. Consumers C maximise rents given a certain demand function. During recourse, they decide on their consumption level and trade flows. Consumers behave in a price-taking way.

3. Strategic player M jointly maximises both its consumer rent and producer rent through its recourse variables of consumption, supply and trade flows. M is therefore a consumer as well as a producer in its own right. The development of its demand and capacity stock is assumed to be given. Since we assume that capacity additions for producing regions of M follow a predetermined schedule, M does not have to make investment decisions. M maximises its payoff, given supply and demand of a competitive fringe of other players. It therefore acts as a monopsonist for investors I and as a monopolist for other consumers C. With this setup, we model the Chinese export and import control system under the assumption that they serve domestic welfare maximisation. It is important to note that, in our setup, we assume that M is a national player (e.g., it exerts market power through national export and import controls only vs. other players). Individual companies on the demand and the supply side do not exert market power and behave in a price-taking manner.

Figure 5.1 depicts the possible interactions of model players as well as the timing of investment decisions and the information structure. We assume that investors have to decide if they want to invest into new capacity before they know the precise demand level. To model this situation, we introduce uncertainty into the model by assuming that demand level of M is not foreseeable by investors I when capacity investments have to be taken. However, we assume that the distribution of future demand of M, and thus realisation probabilities, are given and known to investors. The first stage thus includes the investment decision stage for investors given a future demand distribution. In the second stage, capacity investments are realised and all players engage in a trading game in which the strategic player exerts market power both versus investors and consumers while the other actors behave as price takers. As demonstrated by Kolstad and Burris (1986), Salant (1982) and recently Lise and Krusemann (2008) and Montero and Guzman (2010), different types of Cournot games can be mapped by a term that is a producer's (consumer's) conjecture about the response of other producers (consumers) to a change in their production (consumption) volume[67]. The two-stage stochastic model concept

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[67] Our model formulation can be interpreted as a quota system that restricts exports or imports to the Cournot-Nash outcome. Other formulations with taxes instead of quotas of course yield the same equilibrium (see e.g.: Kolstad and Abbey, 1984).

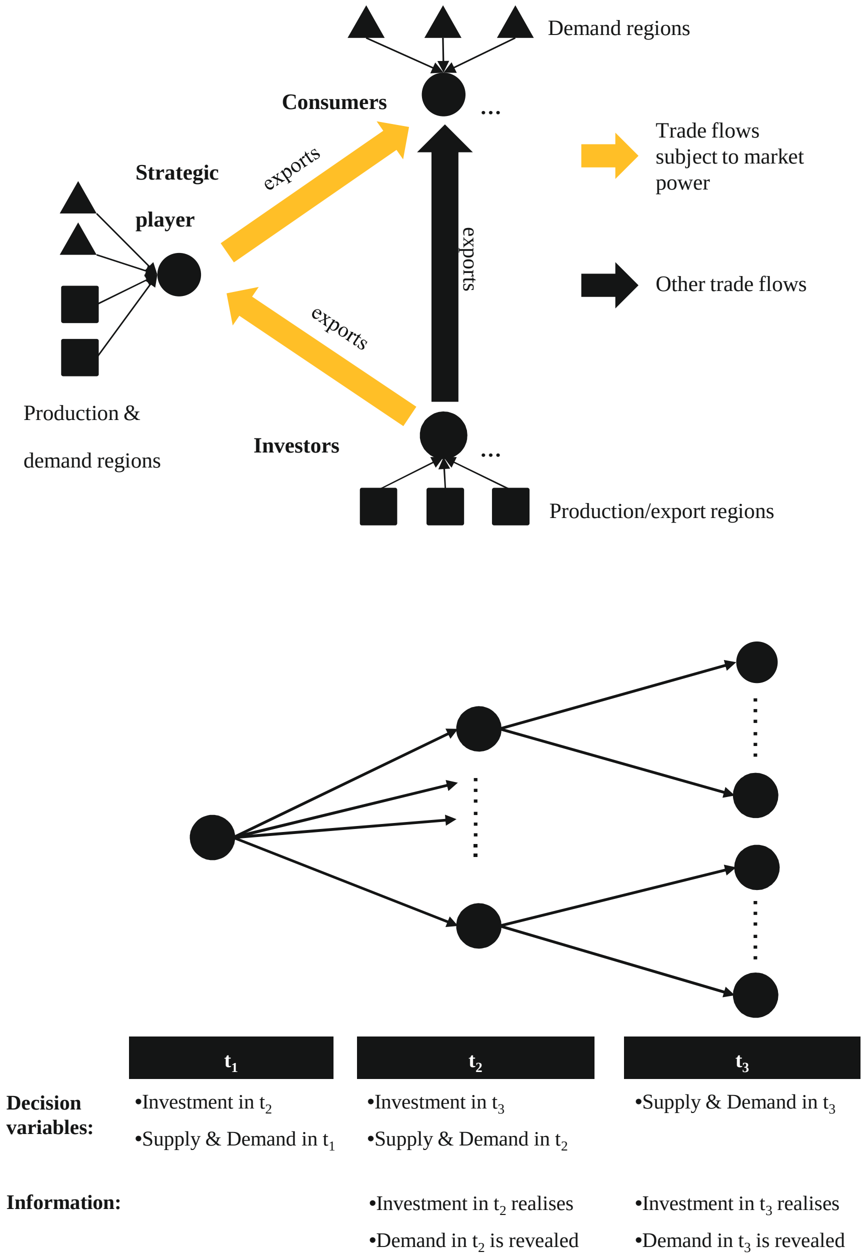

FIGURE 5.1: Setup of modelled players (top) and timing of investment decisions and information structure for a three-period example (bottom).

can be easily generalised to a multi-stage setup as shown in Section 5.3.3. The model is formulated in its extensive form; e.g., all considered futures $n \in N$, or scenarios, and their respective realisation probabilities ω_n, are explicitly accounted for and known. This allows us to represent the information structure of the model as a so-called scenario tree.

Haurie et al. (1990) showed that such a stochastic equilibrium programming approach yields a special class of strategies which the authors call *S-adapted open-loop*. It can basically be regarded as an open-loop equilibrium with uncertainty, where strategies are conditional on the realisation of a stochastic underlying model parameter[68]. The equilibrium is not subgame perfect and players commit themselves to their decisions at the beginning of the game. The equilibrium concept can be useful in analysing long term supply and demand decisions under uncertainty without running into the computational challenges of determining closed-loop strategies. Genc et al. (2007) and Genc and Zaccour (2011) further analysed investment dynamics under uncertain demand and the equilibrium concept has been used in several recent empirical studies, as in Pineau and Murto (2003), Genc et al. (2007) or Bernard et al. (2008).

5.3.2 Risk-adjusted discount factors

As demand realisation is risky, we allow investors I to price their systematic risk in accordance to standard CAPM theory (e.g.: Armitage, 2005). Pricing in systematic risk[69] will cause investors in our model to assume risk-averse behaviour in a sense that they will demand a higher (lower) capital return from expected payoffs of scenario nodes with high (low) market returns r_n^m and low (high) realisation probabilities ω_n. In our case, scenarios with high market returns coincide with high Chinese coal demand as both are driven by economic growth. Thus, the relative weight of expected payoffs from such high demand scenarios diminishes in our model, as they are discounted more strongly. Vice versa, the relative weight of low demand scenarios increases.

For implementation, we rely on a methodology described by Fama (1977) to compute deterministic equivalents of risky cash flows using linear stochastic discount factors. Stochastic discount factors $d^s(n)$ are defined such that a cash flow vector $X(n)$ accruing in a later time period has the value $E[d^s(n) \times X(n)]$ at time period 0. If one relies on the theories and assumptions of CAPM, such a vector may be determined ex-ante if the vector of market returns and the risk-free interest rate r^f are known. Using stochastic discount factors enables us to compute the equivalent deterministic cash flows in each scenario so that any further intertemporal discounting of pay-offs may be done at the risk-free interest rate. A very comprehensive overview of how to implement the notion of deterministic equivalent cash flows into stochastic equilibrium models has been provided by Ehrenmann and Smeers (2010). In this analysis, we largely follow their approach.

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[68] But not on realisations of other players decisions.

[69] Systematic risk is the not diversifiable risk that is associated with aggregate market returns. In contrast, unsystematic risk is company or industry-specific and is not correlated with market returns. It may be reduced through portfolio diversification (Armitage, 2005).

5.3.3 Model formulation

The information structure of the model is represented by a scenario tree which consists of a set of scenario nodes $n \in N$. Let $succ(n)$ represent the set of all successor scenario nodes to scenario node n and let $pred(n)$ be the set of all predecessor scenario nodes of n. The spatial topology of the model consists of export regions $e \in E$, demand regions $d \in D$ and transport routes $(e, d) \in A \subset E \times D$. Each investor $i \in I$ controls a set of export regions $e \in E_i$ and each consumer $c \in C$ controls a set of demand regions $d \in D_c$. The monopolist $M = \{m\}$ controls export regions as well as demand regions. We assume quadratic costs functions and linear demand functions as well as constant investment- and transport costs. An overview of all sets, decision variables and parameters can be found in Table 5.1.

The remainder of this section is organised as follows: We develop the optimisation problems and the corresponding first-order optimality conditions for each player type. The first-order conditions together with the market-clearing conditions bundled together form the stochastic equilibrium model.

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 the perpendicular sign $\perp$, where $0 = x \perp y = 0 \Leftrightarrow x^t y = 0$ for vectors x and y.

The investors' problem

Each investor $i \in I$ maximises its profit which is defined as revenue minus costs of supply and minus investment costs. Investors behave as price takers in the market. The payoff function $\Pi_i^I(z_i)$ is defined as:

$$\max_{z_i \in \Omega_i} \Pi_i^I(z_i) = \sum_{n \in N} \omega_n d_n^S d_n^F \sum_{e \in E_i} \left[p_{e,n}^{Ex} s_{e,n} - \left(a_{e,n} s_{e,n} + \frac{1}{2} b_{e,n} s_{e,n}^2 + c_{e,n}^{Inv} x_{e,n} \right) \right], \quad (5.1)$$

where z_i is the corresponding decision vector of i. Ω_i is the set of feasible solutions of z_i and is defined by constraints for maximum supply:

$$Cap_e^{Start} + \sum_{n' \in pred(n)} x_{e,n'} - g_e \sum_{n' \in pred(n)} s_{e,n'} - s_{e,n} \geq 0, \qquad (\epsilon_{e,n}) \qquad \forall\, e \in E_i,\ n \in N, \quad (5.2)$$

TABLE 5.1: Model sets, variables and parameters.

Sets	
$e \in E$	export regions
$d \in D$	demand regions
$i \in I$	Investors
$c \in C$	Consumers
$e \in E_i$	export regions controlled by investor i
$d \in D_c$	demand regions controlled by consumer d
$d \in D_M$ and $e \in E_M$	demand and export regions of strategic player M
$n \in N$	scenario nodes
$n \in succ(n')$	set of all scenario nodes which are successor nodes to n'
$n \in pred(n')$	set of all scenario nodes which are predecessor nodes to n'
Primal variables	
$x_{e,n}$	investments
$s_{e,n}$	supply
$t_{(e,d),n}$	trade flows
$y_{c,d,n}$	consumption
$p^{Ex}_{e,n}$	export price
$p^{Im}_{d,n}$	consumer price
$a_{e,n}$	marginal cost intercept
$b_{e,n}$	marginal cost slope
$k^M_{d,n}$	total sales volume of M
$l^M_{e,n}$	total import volume of M
Dual variables	
$\epsilon_{e,n}$	dual variable for investments
$\lambda_{e,n}$	dual variable for supply
$\mu_{e,n}$	dual variable for maximum capacity
$\rho_{d,n}$	dual variable for consumption
$\sigma_{d,n}$	dual variable for total sales volume
$\delta_{e,n}$	dual variable for total import volume
Parameters	
ω_n	probability of scenario node n
d^S_n	stochastic discount factor of scenario node n
d^F_n	risk-free discount factor of scenario node n
Cap^{Start}_e	initial capacity of export region e
Cap^{Max}_e	maximum capacity of export region e
$Cap^M_{e,n}$	capacity of strategic player M in export region e
a^{Start}_e	initial marginal cost intercept of export region e
b^{Start}_e	initial marginal cost slope of export region e
g_e	exploitation factor of export region e
h_e	investment effect on marginal costs of export region e
$u_{e,n}$	input cost increase of export region e
$c^{Inv}_{e,n}$	investment costs for export capacity of export region e
$c^T_{(e,d)}$	transport costs on transport route (e,d)
$v_{d,n}$	demand intercept for demand region d
$w_{d,n}$	demand slope for demand region d

and by constraints for maximum investments:

$$Cap_e^{Max} + g_e \sum_{n' \in pred(n)} s_{e,n'} - Cap_e^{Start} - \sum_{n' \in pred(n)} x_{e,n'} \geq 0, \ (\mu_{e,n}) \ \forall\, e \in E_i, \ n \in N. \quad (5.3)$$

Each investor thus faces a dynamic multistage investment problem where investments have to be decided upon before demand is realised in later scenario nodes. The first-order conditions of the investors' problem can then be summarised by constraints (5.2) and (5.3) as well as the following:

$$\omega_n d_n^S d_n^F \left(p_{e,n}^{Ex} - a_{e,n} - b_{e,n} s_{e,n}\right) - \epsilon_{e,n} - \mu_{e,n} \leq 0 \perp s_{e,n} \geq 0, \qquad \forall\, e \in E_i, \ n \in N, \quad (5.4)$$

$$\omega_n d_n^S d_n^F c_{e,n}^{Inv} - \sum_{n' \in succ(n)} \epsilon_{e,n'} \leq 0 \perp x_{e,n} \leq 0, \qquad \forall\, e \in E_i, \ n \in N. \quad (5.5)$$

We implement the concept of dynamic short run marginal costs functions which has first been described by Haftendorn et al. (2010). In their work, the authors model marginal costs endogenously as a function of cumulative supply and investments. Increases in cumulative supply increases the marginal cost intercept as the cheapest reserve deposits get exhausted. Increases in cumulative investments may have ambiguous effects depending on the age of the mining basin and the remaining reserves. In their paper, Haftendorn et al. (2010) apply their methodology to a linear marginal cost function, and we follow the same approach. The endogenous evolution of the marginal cost intercept is then described by:

$$a_{e,n} = u_{e,n} \left(a_e^{Start} + g_e \sum_{n' \in pred(n)} b_{e,n} s_{e,n} \right), \qquad \text{(free)} \qquad \forall\, e \in E_i, \ n \in N, \quad (5.6)$$

and the evolution of the marginal cost slope by:

$$b_{e,n} = u_{e,n} \left(b_e^{Start} + h_e \sum_{n' \in pred(n)} x_{e,n} \right), \qquad \text{(free)} \qquad \forall\, e \in E_i, \ n \in N. \quad (5.7)$$

We assume that there is no arbitrage between supply and trade and that the mass balance in all export regions of investors always has to be satisfied:

$$s_{e,n} = \sum_{d \in D} t_{(e,d),n}, \qquad \text{(free)} \qquad \forall\, e \in E \backslash E_M,\ n \in N. \tag{5.8}$$

The consumers' problem

We assume that consumers behave in a competitive manner such that they take prices as given[70]. We further assume that consumers cannot generate savings or build up coal stocks. Therefore, in each scenario node $n \in N$ each consumer faces a static maximisation problem, as there are no intertemporal decisions to be taken. Consumer payoff is defined as gross surplus less costs of procurement. The payoff function $\Pi^C_c(z_c)$ is defined as:

$$\begin{aligned} \max_{z_c \in \Omega_c} \Pi^C_{c,n}(z_c) = \sum_{d \in D_c} \Bigg[& \int_0^{y_{d,n}} p^{Im}_{d,n}(u)\mathrm{d}u \\ & - \sum_{e \in E \backslash E_M} \left(p^{Ex}_{e,n} + c^T_{(e,d)} \right) t_{(e,d),n} - \sum_{e \in E_M} p^M_{d,n} t_{(e,d),n} \Bigg], \qquad \forall\, n \in N. \end{aligned} \tag{5.9}$$

Each consumer procures his consumption directly from the investors I (first term of second line (5.9)), thus paying export prices plus shipping costs. In case of procurements from M, consumers pay the respective import price $p^M_{d,n}$ that M is setting. This will later become important when we derive the conditions for the equilibrium. Linear inverse demand is defined as $p^{Im}_{d,n}(y_{d,n}) = v_{d,n} + w_{d,n} y_{d,n}$. We compute the parameters of the demand function using a reference demand level D_{ref}, a reference price p_{ref}, and elasticity e. The slope of the demand function can then be expressed as $w_{d,n} = \frac{p_{ref}}{D_{ref}} \frac{1}{e}$ and the demand intercept through $v_{d,n} = p_{ref} - w_{d,n} D_{ref}$. Assumptions on reference volumes, prices and elasticities can be found in the Appendix. Consumers face the constraint that inbound trade flows have to be greater or equal to consumption:

$$\sum_{e \in E} t_{(e,d),n} - y_{d,n} \geq 0, \qquad (\rho_{d,n}) \qquad \forall\, d \in D_c,\ n \in N. \tag{5.10}$$

First-order conditions for consumer c are equation (5.10) and:

$$p^{Im}_{d,n}\left(y_{d,n}\right) - \rho_{d,n} \leq 0, \perp y_{d,n} \leq 0, \qquad \forall\, d \in D_c,\ n \in N, \tag{5.11}$$

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[70] As consumers represent a large number of national utility companies as well as many different energy-intensive industries we conclude that there is little potential for consumers to exercise market power on the international coal market.

$$\rho_{d,n} - p^{Ex}_{e,n} - c^{T}_{(e,d)} \leq 0 \perp t_{(e,d),n} \leq 0, \qquad \forall\, d \in D_c,\ n \in N,\ e \in E \backslash E_M, \tag{5.12}$$

$$\rho_{d,n} - p^{M}_{d,n} \leq 0 \perp t_{(e,d),n} \leq 0, \qquad \forall\, d \in D_c,\ n \in N,\ e \in E_M. \tag{5.13}$$

The strategic player's problem

The strategic player M controls demand regions as well as export regions. Demand regions of M are specified through linear demand functions (similarly as for consumers), and supply regions are specified by quadratic cost functions and a capacity limit. Potential imports or exports balance M's supply and demand. M uses its imports and exports as strategic variables to maximise its total welfare, the joint surplus of production and consumption. Its maximisation problem is static, as we assume a fixed trajectory for its export capacity evolution[71], therefore no intertemporal decisions are taken[72]. Its payoff $\Pi^{M}(z_M)$ is defined as:

$$\begin{aligned}\max_{z_M \in \Omega_M} \Pi^{M}_{n}(z_M) = & \sum_{d \in D \backslash D_M} p^{M}_{d,n}\,(.)\, k^{M}_{d,n} - \sum_{e \in E_M} \left(\sum_{d \in D} c^{T}_{(e,d)} t_{(e,d),n} + a_{e,n} s_{e,n} + \frac{1}{2} b_{e,n} s^{2}_{e,n} \right) \\ & + \sum_{d \in D_M} \int_{0}^{y_{d,n}} p^{Im}_{d,n}(u)\mathrm{d}u - \sum_{e \in E \backslash E_M} \left(\sum_{d \in D_M} c^{T}_{(e,d)} t_{(e,d),n} + p^{Ex}_{e,n} l^{M}_{e,n} \right) \\ & \forall n \in N. \end{aligned} \tag{5.14}$$

M's total welfare is defined as export sales to consumers C less transport costs for outbound flows and production costs (first line of (5.14)) plus total gross consumer surplus minus transport costs for imports and procurement costs from investors I (second line of (5.14)). M's production capacity constraint is:

$$Cap^{M}_{e,n} - g_e \sum_{n' \in pred(n)} s_{e,n'} - s_{e,n} \geq 0, \qquad (\epsilon_{e,n}) \qquad \forall\, e \in E_M,\ n \in N. \tag{5.15}$$

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[71] This will be explained in more detail in Section 5.4.

[72] We therefore neglect that M might be able to anticipate how production cost functions of investors I are affected given M's consumption and import decisions. If M decides to import more in earlier periods production costs among investors increase as the cheapest seams get exploited (modelled through equation (5.6)). This would increase M's cost for importing in later periods. While this mechanism seems to be worthwhile to investigate further, it is beyond the scope of this analysis.

The energy balance for M's production regions is:

$$s_{e,n} - \sum_{d \in D} t_{(e,d),n} \geq 0, \qquad (p^{Ex}_{e,n}) \qquad \forall\, e \in E_M,\ n \in N. \tag{5.16}$$

The energy balance for M's demand regions is:

$$\sum_{e \in E} t_{(e,d),n} - y_{d,n} \geq 0, \qquad (\rho_{d,n}) \qquad \forall\, d \in D_M,\ n \in N. \tag{5.17}$$

The energy balance for all exports of M to consumers I is:

$$\sum_{e \in E_M} t_{(e,d),n} - k^M_{d,n} \geq 0, \qquad (\sigma_{d,n}) \qquad \forall\, d \in D \backslash D_M,\ n \in N, \tag{5.18}$$

and the energy balance for all imports of M from investors I is:

$$\sum_{d \in D_M} t_{(e,d),n} - l^M_{e,n} \geq 0, \qquad (\delta_{e,n}) \qquad \forall\, e \in E \backslash E_M,\ n \in N. \tag{5.19}$$

The first-order conditions of M with respect to supply, physical trade flows and consumption are:

$$p^{Ex}_{e,n} - \epsilon_{e,n} - (a_{e,n} + b_{e,n} s_{e,n}) \leq 0 \perp s_{e,n} \geq 0, \qquad \forall\, e \in E_M,\ n \in N, \tag{5.20}$$

$$\sigma_{d,n} - c^T_{(e,d)} - p^{Ex}_{e,n} \leq 0 \perp t_{(e,d),n} \geq 0, \qquad \forall\, e \in E_M,\ d \in D \backslash D_M,\ n \in N, \tag{5.21}$$

$$\rho_{d,n} - c^T_{(e,d)} - p^{Ex}_{e,n} \leq 0 \perp t_{(e,d),n} \geq 0, \qquad \forall\, e \in E_M,\ d \in D_M,\ n \in N, \tag{5.22}$$

$$\delta_{e,n} - c^T_{(e,d)} - p^{Ex}_{e,n} + \rho_{d,n} \leq 0 \perp t_{(e,d),n} \geq 0, \qquad \forall\, e \in E \backslash E_M,\ d \in D_M,\ n \in N, \tag{5.23}$$

$$p^{Im}_{d,n}(y_{d,n}) - \rho_{d,n} \leq 0 \perp y_{d,n} \geq 0, \qquad \forall\, e \in E\ , d \in D_M,\ n \in N. \tag{5.24}$$

The first-order condition w.r.t export sales $k^M_{d,n}$ of M is given by:

$$p^M_{d,n} + \frac{\partial p^M_{d,n}}{\partial k^M_{d,n}} k^M_{d,n} - \sigma_{d,n} \leq 0 \perp k^M_{d,n} \geq 0, \qquad \forall\, d \in D \backslash D_M.\ n \in N, \tag{5.25}$$

We can now further simplify this pricing equation. We know due to equations (5.11) and (5.13) that $p^M_{d,n} = p^{Im}_{d,n}\,(y_{d,n})$ if $t_{(e,d),n}$ and $y_{d,n}$ are greater zero. Both $y_{d,n}$ and $k^M_{d,n}$ can be substituted by $t_{(e,d),n}$ (see (5.18) and (5.10). As we also know the functional form of

$p^{Im}_{d,n}\left(y_{d,n}\right)$, we can substitute:

$$\frac{\partial p^{M}_{d,n}}{\partial k^{M}_{d,n}} = \frac{\partial p^{Im}_{d,n}\left(\sum_{e\in E} t_{(e,d),n}\right)}{\partial k^{M}_{d,n}} = w_{d,n} \qquad \forall\, d \in D\backslash D_M,\ n \in N, \tag{5.26}$$

which is the usual result that monopolists perceive demand downward sloping and can thus extract a rent by withholding volumes. As we assumed a linear inverse demand function, M's markup is a function of the demand slope $w_{d,n}$ in each demand region. Given equilibrium condition (5.21) we can now rewrite (5.25):

$$p^{Im}_{d,n}\left(y_{d,n}\right)+w_{d,n}k^{M}_{d,n}-c^{T}_{(e,d)}-p^{Ex}_{e,n} \leq 0 \perp k^{M}_{d,n}\wedge t_{(e,d),n} \geq 0,\ \forall\, d \in D\backslash D_M,\ e \in E_M,\ n \in N. \tag{5.27}$$

The first order condition w.r.t import procurements $l^{M}_{e,n}$ of M is given by:

$$-\frac{\partial p^{Ex}_{e,n}}{\partial l^{M}_{e,n}} l^{M}_{e,n} - \delta_{e,n} \leq 0 \perp l^{M}_{e,n} \geq 0, \qquad \forall\, e \in E\backslash E_M,\ n \in N. \tag{5.28}$$

Equation (5.28) can be simplified in a similar manner as (5.26). According to (5.4), $p^{Ex}_{e,n}$ is, among others, a function of $s_{e,n}$. $s_{e,n}$ and $l^{M}_{e,n}$ can both be substituted through $t_{(e,d),n}$ (equations (5.8) and (5.19)) so that we may write:

$$\frac{\partial p^{Ex}_{e,n}}{\partial l^{M}_{e,n}} = \frac{\partial p^{Ex}_{e,n}\left(\sum_{d\in D} t_{(e,d),n}\right)}{\partial l^{M}_{e,n}} = b_{e,n} \qquad \forall\, e \in E\backslash E_M,\ n \in N. \tag{5.29}$$

Oligopsonists perceive the production cost function upward sloping and can thus extract a rent by consuming less (e.g., through implementing import taxes (Kolstad and Abbey, 1984)). For a linear marginal cost function, M's markup depends on the marginal cost slope $b_{e,n}$. Given equilibrium conditions (5.23) and (5.24), (5.28) may be written as:

$$p^{Im}_{d,n}\left(y_{d,n}\right) - b_{e,n}l^{M}_{e,n} - c^{T}_{(e,d)} - p^{Ex}_{e,n} \leq 0 \perp l^{M}_{e,n} \wedge t_{(e,d),n} \geq 0,\ \forall\, e \in E\backslash E_M,\ d \in D_M,\ n \in N. \tag{5.30}$$

The combined equilibrium conditions of investors, consumers, and the strategic player yield a unique equilibrium. The resulting set of inequalities is known as a mixed complementarity problem.

5.4 Computational application

To illustrate how uncertainty and demand side market power affect investors, we conduct a case study for the global steam coal market for reference years 2015 and 2020. China takes over the role of the strategic player M. Other coal importers are modelled as consumers and the major coal exporters as investors. We use a large existing database on global coal markets which has been extensively presented in Paulus and Trüby (2011), Trüby and Paulus (2011) and which has also been used by IEA (2011b). Based on the present data, we make assumptions on the projected evolution of parameters such as reference demand and reference prices in consumer regions, and mining input factor prices. The model consists of more than 30 demand and export regions. A detailed overview of these parameter assumptions can be found in the Appendix.

The model has been implemented in GAMS and is solved using the PATH solver (Ferris and Munson, 1998).

5.4.1 Scenario tree definition

Evolution of China's demand is described by a set of scenarios which describe a wide range of possible trajectories. The basis for developing the demand scenarios is the Chinese 12th 5-Year Plan. The plan sets very challenging targets to be reached by 2015, including a reduction of energy intensity by 16% and an increase of non-fossil energy production to 11%. Most importantly, the target for economic growth was set to 7% p.a., down by 2% from the last 5-year plan (real economic growth rates were even higher, according to IMF (2011), more than 10% between 2005-2010). Chinese coal demand is driven by economic growth, energy intensity, and the ramp-up speed of renewables and other energy sources in China. Therefore, achieving the plan's targets would significantly reduce coal demand growth. However, reaching these goals would also be very challenging. Additionally, these targets are not considered 'binding' in the plan and therefore may be demoted to achieve other targets (e.g., inflation containment).

Taking the Chinese 12th 5-Year Plan as the reference scenario for the lowest coal demand evolution until 2015 (scenario node l in Figure 5.2), we construct two further scenarios for 2015. In one scenario, we assume economic growth to be 9% (scenario node m) and in another other scenario, we also assume 9% economic growth and additionally reduced gains in energy efficiency (scenario node h). Coal demand[73] is derived from multiplying

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[73] The term 'coal demand' refers to a reference coal demand that is consumed at a certain reference price. Together with an assumption on demand elasticity, it is possible to construct linear demand functions. Reference coal demand, reference prices, and elasticities for all regions are provided in the Appendix.

the different GDP trajectories with energy intensity assumptions and deducting the projected expansion of renewables and other fossil fuels. The remainder of energy demand has to be covered by coal. In the next time step until 2020, we assume economic growth to either be 8% p.a. (scenario nodes *hh*, *mh* and *lh*) or 6% (scenario nodes *hl*, *ml* and *ll*). Altogether, the ten scenario nodes form six scenarios paths, which we label *s1* to *s6*. We assume realisation probabilities are uniformly distributed. A summary of the Chinese energy balances can be found in the Appendix.

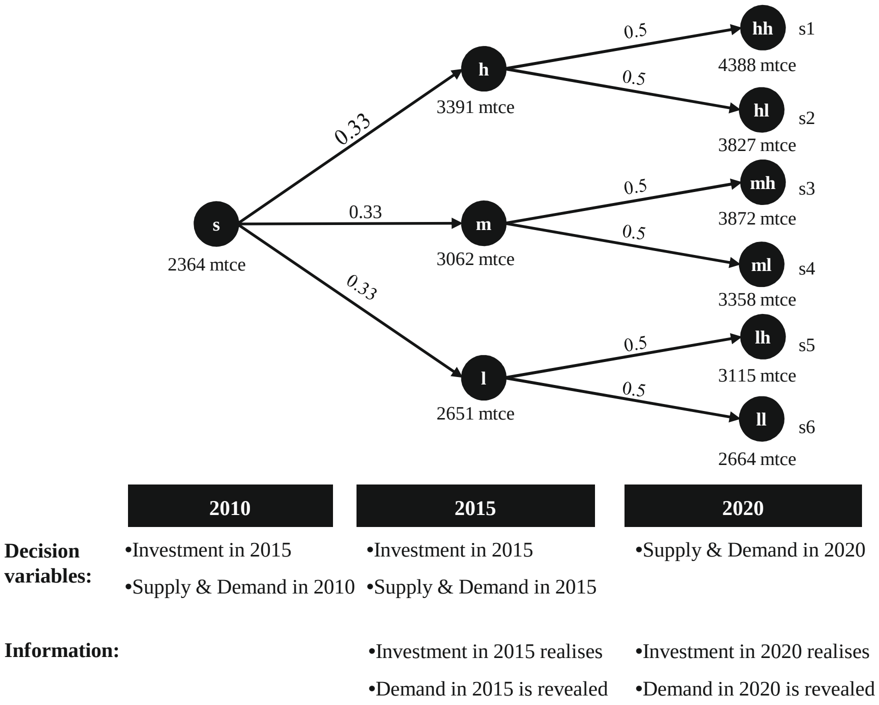

Figure 5.2: Scenario tree structure and information structure of the model. Demand figures are given in million tonnes of coal equivalent [mtce] and have to be understood as reference demand levels given a certain reference price.

The expansion of coal supply of China is outlined in the 12th 5-Year Plan. We assume that the ambitions and incentives of the Chinese coal industry to fulfil the plan's targets are a more important driver than just pure market economics. Therefore, Chinese coal supply capacity in the model follows the production targets of the 12th 5-Year Plan. Supply is projected to increase by another 30% between 2010 and 2015. This is already an ambitious target, as the Chinese coal industry is currently undergoing a profound restructuring process. Thus, China is expanding its domestic capacity at the fastest rate possible.

To compute stochastic discount factors, we assume a risk-free interest rate of 3.5%. Market returns are assumed to be correlated with Chinese economic growth. For details regarding the stochastic discount factors please refer to the Appendix.

5.4.2 Scenarios and outline of result discussion

For model discussion, we test two setups. In the first scenario, we assume that the strategic player M behaves as a simple price taker both on the export and the import side (*competitive setup*). Thus, M basically becomes a player of the consumer type with an attached supply base. In the second setup, M behaves as a monopolistic/monopsonistic player for exports and imports (*Monop setup*). We will structure the comparison of the scenario results into two steps. First, we will investigate how investment decisions of investors change. Second, we will analyse how costly uncertainty is for investors by computing the Value of Perfect Information (VPI). In both steps we will compare the stochastic model to its deterministic version.

5.5 Simulation results and discussion

Model results for investments and payoffs are summarised in Tables 5.2 and 5.3. We first compare the stochastic *competitive setup* with its deterministic equivalent. For this, we compute the expected model results under perfect information, which means we sum up the weighted outcomes of the deterministic model run for each of the scenarios *s1* to *s6* and compare them to the stochastic model run. The weighted deterministic results for the *competitive setup* are referred to as 'comp-det' and for the *Monopoly setup* as 'mon-det', respectively. The results of of the stochastic model are referred to as 'comp-stoch' and 'mon-stoch'.

5.5.1 Investments

Two effects are noteworthy if we look at the model results for investments: In the *competitive setup*, the expected total amount of investments of 395 mtpa does not essentially change compared to the deterministic baseline (see 'weighted sum' and lines 'comp-det.' and 'comp-stoch.' in Table 5.2). However, investments change with respect to their spatial as well as their temporal allocation. In the first investment stage s, total investments with 198 mtpa are 8% lower in the stochastic model compared to those of its deterministic counterpart. The investors hedge themselves against risky demand by delaying investments until a later stage where they have a higher certainty that their investments will become profitable. This effect is strengthened by the fact that investors price their systematic risk and thus emphasise asset returns of the lower demand scenario nodes higher than the ones from the higher demand nodes.

Table 5.2: Investments in export capacity in mtpa, stochastic model runs and deterministic equivalents.

Countries[a]:		IR	VN	SA	CO	PL	VE	QLD	NSW	R e.	R w.	US	$\sum$
s[b]	comp-det	90	11	10	32	1	10	0	59	2	0	0	**214**
(2010)	comp-stoch	76	11	0	32	0	11	0	69	0	0	0	**198**
	mon-det	30	11	0	32	0	10	0	39	0	0	0	**122**
	mon-stoch	12	11	0	32	0	11	0	20	0	0	0	**85**
l	comp-det	81	2	18	5	2	1	0	38	0	0	0	**146**
(2015)	comp-stoch	0	2	0	5	0	1	0	0	0	0	0	**8**
	mon-det	80	2	2	5	0	1	0	50	0	0	0	**140**
	mon-stoch	12	2	0	5	0	1	0	46	0	0	0	**66**
m	comp-det	50	2	35	5	7	1	34	8	31	16	8	**196**
(2015)	comp-stoch	72	2	35	5	9	1	53	7	44	24	14	**267**
	mon-det	102	2	8	5	2	1	0	32	0	0	0	**151**
	mon-stoch	132	2	35	5	4	1	0	54	0	0	0	**233**
h	comp-det	21	2	4	5	7	1	53	8	37	30	26	**194**
(2015)	comp-stoch	72	2	35	5	11	1	55	7	44	34	28	**295**
	mon-det	105	2	16	5	3	1	0	26	0	0	0	**157**
	mon-stoch	132	2	22	5	4	1	0	54	0	0	0	**219**
wtd.	comp-det	140	12	30	36	6	12	30	76	26	15	11	**395**
$\sum$	comp-stoch	127	12	25	36	7	11	38	74	31	20	14	**395**
	mon-det	126	12	8	36	2	12	0	75	0	0	0	**272**
	mon-stoch	108	12	21	36	3	11	0	72	0	0	0	**263**

[a] Country abbreviations: IR - Indonesia, VN - Viet Nam, SA - South Africa, CO - Colombia, PL - Poland, VE - Venezuela, QLD - Queensland (Australia), NSW - New South Wales (Australia), R e. - Russia east coast, R w. - Russia west coast, US - United States.

[b] Investments take place with a time lag of one time period: investment decisions taken in 2010 (scenario node s) become available in 2015 (scenario nodes l, m, and h). Investments decisions taken in 2015 become available in 2020 (scenario nodes ll, lh, ml, mh, hl and hh).

The picture becomes somewhat more complex in the second investment stage (scenario nodes l, m, and h). In scenario nodes m and h, where higher demand has been realised investors in the stochastic model catch up their investments which they have been delaying thus far. Investments in m and h are 36% and 52% higher than in the deterministic model, respectively. On the contrary, investments in the stochastic model in scenario node l, where low demand is realised, are close to zero and significantly below those of the deterministic counterpart. This is also due to the hedging decision investors faced in s; as investors do not want to forego possible returns from m and h completely, they invest at a level in s which is above the optimal value for scenario node l. In contrast, investors in the deterministic models invest 40% less in s for the low demand trajectory.

In addition to the intertemporal hedging effect changing spatial allocation of investments is also driven by a technological hedging effect. Export regions are characterised by their (linear) marginal cost function and their investment costs for capacity additions. Roughly, export regions can be classified as either belonging to a low-cost type or a high-cost type; low-cost types have low investment costs, low marginal cost intercepts but higher marginal cost slopes (marginal costs rising fast). High-cost types have high investment costs, higher marginal cost intercepts but lower marginal cost slopes. Naturally, the low-cost type regions are more suited to handle low demand scenarios and the high-cost type regions are better fitted for high demand scenarios. Of course, some regions are a mix of both types. Investors in the stochastic model invest in a portfolio of export capacities given their valuation of expected payoffs to hedge against different potential demand levels. This can be seen from the distribution of investments over regions (see lines 'comp-det.' and 'comp-stoch.' in Table 5.2): Indonesia and South Africa capture smaller shares of investments in the stochastic model, while investments in Queensland, Russia and the U.S. increase by 20% to 30%.

Expected investments in the *Monopoly setup* are 272 mtpa and 263 mtpa - around 30% lower than in the *Competitive setup* (in the deterministic and in the stochastic case). In the *Monopoly setup*, China behaves in a Monopolistic fashion both on the export and the import side. Due to high demand compared to supply in practically all scenarios nodes, exports of China are mostly negligible; this means that supply-side market power potential is low. On the other hand, imports of China vary widely between the *Competitive setup* and the *Monopoly setup*, indicating the demand-side market power potential of China. This leads to a reduction of its procurements from investors, lower export prices, and thus a reduced incentive for investors to invest in new capacity. Also, the temporal hedging effect is even stronger here; in the first investment stage s, total investments are 31% lower in the stochastic model compared to its deterministic counterpart, while they were 8% lower in the *Competitive setup.*

The driver for lower investments in the *Monopoly setup* is that China accrues monopolistic rents by withholding consumption from the market. This reduces rents of investors due to lower overall seaborne demand and trade market prices (an overview of import region prices is provided in the Appendix). It is thus less attractive for investors to invest in new capacity in the *Monopoly setup*, as they anticipate that China will adjust its imports and thus reduces payback for their investments. The amount of monopolistic rents accrued by China depends on the slope of investors' marginal cost functions and the slope of the Chinese demand functions, which both vary by region.

In summary, we may therefore conclude that investors reallocate their investments spatially and temporally to hedge themselves against risky Chinese demand outcomes. However, under the assumed parameter setup, the amount of investments is not affected. On the other side, the exertion of Chinese market power in fact leads to lower investments, as China's welfare maximising strategy is to withhold foreign imports, thus lowering seaborne prices and trade market demand and making investments less profitable.

5.5.2 Value of Perfect Information

As described, investors in the stochastic model adapt their investment decisions to risky demand outcomes. This means that the portfolio of investment decisions generates the highest returns, given all demand scenarios and their respective realisation probabilities. However, investment decisions are not optimal with respect to each individual scenario. The associated costs are commonly referred to as the value of perfect information, or VPI[74], and are calculated by subtracting the payoff of the stochastic model from the probability weighted sum of payoffs of the deterministic models for each scenario (Birge and Louveaux, 1997). Table 5.3 shows the VPI as a ratio of deterministic payoffs of the different models and players.

In the *Competitive setup*, all players exhibit a positive VPI. Investors have the highest VPI, making up 17.6% of the payoffs in the deterministic models (see Table 5.3 section 'Comp', line 'Investors' right hand column), as they have to decide on investments under risky demand. The high costs of uncertainty for investors is explained by the range of Chinese coal demand evolutions and their underlying assumptions; as China continues to expand its coal mining capacity at the fastest rate possible, any excess demand has to be covered by imports. However, given the very large market size of China and the strong correlation between economic growth and energy demand Chinese imports vary widely, between 123 mtce in the *ll* scenario node and 519 mtce in the *hh* scenario node in the *Competitive setup*. These variations in imports are very large compared to the relatively small size of the seaborne trade market, which is composed of the investors and consumers. In the *ll* scenario node, Chinese imports make up 15% of total trade against 46% in the *hh* scenario node. As investors have to decide on their investments ex-ante, they hedge against this very large spread of Chinese import demand by delaying investments and forgoing a part of the payoffs that they would realise in the deterministic models.

The hedging effect of investors can also be seen in Table 5.3; the VPI for most investors is strongly *negative* in scenarios with low demand evolutions (*l*, *ll*, *ml* and *hl*), meaning

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[74] In the following we will use the terms *VPI* and *costs of uncertainty* interchangeably.

that investors actually have *higher* payoffs in the stochastic model. However, the VPI for these investors is also strongly positive in the scenarios with high demand evolutions (*h*, *lh*, *mh* and *hh*). If we observe the demand scenarios belonging to each model stage ('2015', '2020'), the effect is partly netted away. Investment costs accrue in the predecessor scenario node, and investors adapt to risky demand by investing more in the low scenario nodes than in the deterministic baseline, and vice versa. As the higher investment costs are not represented in the VPI of nodes where investments are realised, the VPI in low demand nodes can be negative. Additionally, risk aversion strengthens this effect; investors maximise risk-adjusted payoff streams, which means they evaluate payoffs from 'negative' demand scenarios more highly than from more favourable demand scenarios.

At first thought, consumers and China should actually have zero costs of uncertainty, as they face static payoff maximisation problems, which means a lack of intertemporal decision variables. Nevertheless, consumers and China have a positive VPI making up 2% and 4% of deterministic payoffs, respectively. The reason for this lies in the interaction of consumers and China with the investors through imports, which leads to a spillover of costs of uncertainty from investors to the other players. Investors hedge their investment portfolio against risky demand in the stochastic model by delaying investments and changing their spatial allocation. This leads to higher costs of supply as well as a tighter trade market, which both increase imports costs for consumers and for China. The VPI is high in the high-demand scenario nodes, because investments in the stochastic model are lower than in the deterministic ones for high capacity ('s1' and 's2'). This means that capacity is scarcer and consumers are paying a higher scarcity rent for constrained export capacity to investors. Vice versa, the VPI is negative in the low-demand scenario nodes, because investments in the stochastic model are higher in this case.

If we now compare the *Monopoly setup* with the *Competitive setup*, we can observe that the distribution of costs of uncertainty among market players change. In the *Monopoly setup*, the VPI of investors makes up only 10.2% of payoffs compared to 17.6% in the *Competitive setup*. In absolute terms this difference makes up around 10 billion USD_{2010}. On the other side, the VPI of China is 7.3%, significantly higher in the *Monopoly setup* compared to perfect competition. The absolute increase in VPI for China makes up 27 billion USD_{2010}. Total costs of uncertainty for all market players are 14 billion USD_{2010} or 7 billion USD_{2010} higher in the *Monopoly setup*.

The increase of the VPI for China is driven by the risk aversion of investors; in the stochastic model, investors require a risk premium on the paybacks of their investments. This means that, in the high-demand scenario nodes, prices have to be higher to generate

Table 5.3: VPI as a ratio of deterministic payoffs in [%] (a positive number means the VPI is greater zero).

		2015			2020						
	Country[a]:	l	m	h	ll	lh	ml	mh	hl	hh	sum
comp	JA	-2.6	2.9	11.0	1.3	11.2	-1.6	0.7	-0.6	1.2	1.9
	KR	-2.4	2.7	10.3	1.2	10.5	-1.5	0.7	-0.6	1.1	1.8
	TW	-2.4	2.7	10.1	1.1	10.3	-1.4	0.7	-0.6	1.1	1.8
	OA	-2.2	2.5	9.5	1.1	9.8	-1.4	0.6	-0.6	1.0	1.8
	IN	-2.6	3.0	11.2	1.3	11.5	-1.6	0.7	-0.7	1.3	2.4
	EU	-3.0	3.4	12.9	1.5	12.0	-1.8	0.9	-1.7	1.4	2.2
	U.S.	-3.1	3.5	13.0	1.5	12.1	-1.8	0.9	-1.6	1.5	1.0
	LA	-3.1	3.5	13.1	1.5	12.2	-1.8	0.9	-1.5	1.5	2.3
	Consumer	-2.6	3.0	11.2	1.3	11.1	-1.6	0.7	-0.9	1.2	**2.0**
mon	JA	0.5	2.2	2.6	3.9	6.6	-2.0	-1.0	-0.4	-0.2	1.0
	KR	0.5	2.0	2.5	3.7	6.2	-1.9	-0.9	-0.4	-0.2	0.9
	TW	0.5	2.0	2.4	3.6	6.0	-1.8	-0.9	-0.3	-0.2	0.9
	OA	0.4	1.9	2.3	3.4	5.7	-1.7	-0.9	-0.3	-0.2	0.9
	IN	0.5	2.2	2.7	3.9	6.7	-2.0	-1.0	-0.4	-0.2	1.2
	EU	0.6	2.6	3.1	4.3	7.6	-1.7	-1.2	-0.4	-0.3	1.2
	U.S.	0.6	2.6	3.1	4.3	7.6	-1.3	-1.1	-0.4	-0.3	0.6
	LA	0.6	2.6	3.1	4.3	7.7	-1.4	-1.2	-0.5	-0.3	1.3
	Consumer	0.5	2.2	2.7	3.9	6.7	-1.9	-1.0	-0.4	-0.2	**1.1**
comp	IR	-106.3	75.8	28.0	-16.9	49.8	2.1	61.8	-9.1	61.7	17.9
	AU	-102.1	73.5	6.6	-19.9	36.7	0.9	61.8	-9.5	61.6	18.3
	VN	-74.2	74.5	18.1	-19.3	43.7	30.0	62.0	20.8	61.9	18.1
	RU	-18.4	69.8	-8.7	-56.2	-8.9	-19.9	62.1	-10.4	61.2	18.9
	SA	-86.2	72.9	45.4	-21.6	58.8	-3.0	61.8	-8.9	61.7	18.3
	CO	-72.6	74.3	16.2	-19.9	44.0	-2.8	61.8	-4.7	61.8	14.3
	U.S.	-26.6	70.3	-54.7	-46.5	-20.1	-10.7	59.6	-15.3	65.1	16.3
	PL	-85.8	75.0	51.5	-29.4	53.2	-4.8	60.3	-5.3	60.8	20.9
	VE	-66.0	73.6	11.9	-24.0	37.0	13.5	61.6	36.5	61.6	20.0
	Investors	-88.3	74.4	20.0	-20.1	43.5	1.0	61.8	-6.5	61.8	**17.6**
mon	IR	-115.6	77.1	37.9	-23.6	59.0	-0.7	65.3	-9.3	63.2	10.7
	AU	-98.7	77.8	41.0	-47.4	44.2	6.0	65.6	-8.9	63.3	12.3
	VN	-98.6	74.9	30.9	-36.9	49.5	0.0	64.7	-9.5	63.2	9.4
	RU	-112.0	72.0	19.9	-155.7	23.9	-2.3	65.0	-9.2	63.2	6.7
	SA	-103.0	78.0	30.2	-43.0	49.0	-28.6	54.7	-17.8	61.4	6.1
	CO	-98.8	74.8	30.6	-36.3	49.2	-4.3	64.7	-9.6	63.2	9.6
	U.S.	-108.9	72.8	25.7	-129.2	-2.6	24.6	65.0	-8.2	63.4	16.0
	PL	-116.7	80.0	21.2	-65.7	43.4	-16.7	60.2	-21.2	62.0	5.4
	VE	-100.2	74.1	28.5	-50.9	42.4	-1.1	65.5	-8.8	63.3	9.1
	Investors	-105.8	76.2	34.5	-38.9	50.0	-1.7	64.3	-10.0	63.0	**10.2**
comp	PRC	-4.4	5.7	9.3	-1.0	12.3	-1.6	9.2	-1.2	13.2	**3.6**
mon	PRC	-13.3	19.4	16.2	-1.5	19.2	-3.2	19.6	-3.6	26.3	**7.3**

[a] Country abbreviations: JA - Japan, KR - South Korea, TW - Taiwan, OA - Other Asia, IN - India, EU - Europe, U.S. - United States, LA - Latin America. Scenario abbreviations: comp - *Competitive setup*, mon - *Monopoly setup*.

investments compared to the deterministic model. In other words, investment costs are basically higher. China reduces trade market prices through exertion of market power in the deterministic and the stochastic cases by withholding coal imports. However, a similar reduction of prices in the stochastic model and the deterministic model will lead to a stronger reduction of investments in the stochastic case. This effect can be also seen in the investment figures in Table 5.2; in scenario node 's' investments between the *Competitive setup* and the *Monopoly setup* change by -43% in the deterministic model and by -57% in the stochastic model. Lower investments in the stochastic model may lead to lower payoff for China, which is shown by the VPI.

To conclude, losses of investors due to uncertain Chinese demand are significant. Investors adapt to risky Chinese demand evolutions through different investment plans. This adaption process comes at a price; investors' rents are around 18% lower than in the deterministic baseline. Total costs of uncertainty slightly increase if we account for Chinese market market power. Interestingly though, it seems that monopsonistic behaviour causes that costs of uncertainty are transferred from the investors' side to China. The exertion of market power reduces investor's profitability, and therefore investments, significantly more in the stochastic model due to the increase of costs of capital for investments compared to the deterministic case. Overall reduced investment activity raises prices and thus also affects consumer rents in China.

5.6 Conclusions

The optimal timing and sizing of investments given uncertain future market evolutions is an important challenge for capital-intensive industries. This decision problem gets even more complex if we account for demand-side market power. We empirically investigated these questions for investors in the global steam coal market. In this market, investors currently face high uncertainty with respect to future evolution of Chinese import demand. Additionally, China has realigned its resource strategy in recent years and keeps coal imports and exports under tight control through quotas and taxes.

In the scope of this paper, we develop a multi-stage stochastic equilibrium model which allows us to model uncertain Chinese demand in extensive form and where all players maximise their individual payoff functions either subject to a price-taking strategy or a setting in which a single player behaves as a monopolist/monoposonist and the other players act as competitive fringe. The model accounts for risk aversion in the CAPM sense by implementing the concept of stochastic discount factors. We use an established large coal market database and empirically test for four hypotheses regarding the change of investment plans and changes of the VPI. We find that accounting for uncertainty will make investors hedge their investment decisions by delaying investments and by spatially reallocating them. This results in costs of uncertainty for investors of 18% in relation to their deterministic payoffs. If we enable China to exert market power, trade market prices will be lower, thus leading to lower investments into export capacity. Chinese market power also increases the total costs of uncertainty and its allocation among players. In such a setup, costs of uncertainty are higher for China as withholding consumption leads to a comparatively stronger reduction of investments due to risk-averse investment behaviour of investors.

The results show that delaying of additional capacity investments even if faced with probably rapidly rising coal demand is a consistent strategy for coal exporting nations in an economic sense. Such delays are hard to identify in the real world but might already be observable in recent investment figures (ABARES, 2011). Uncertain Chinese coal import demand increases the capital costs for coal mining investments significantly, which may lead to lower investment activity and bottlenecks in the export supply chain. Exporters accrue scarcity rents in the short run in this case, which may help to explain the high margins in the coal mining business in recent years (IEA, 2011c).

For China it would actually be beneficial to try to reduce uncertainty in the market as it will also be affected by the related costs. This is especially true if it chooses to make use of its demand-side market power potential. While this may seem difficult even for Chinese government executives, more transparency in general on Chinese micro- and macroeconomics might help market players to better foresee Chinese coal demand. This is especially true for data availability of Chinese domestic coal consumption and supply.

Further research could focus on two-sided market power where investors also follow non-competitive strategies, or on testing other concepts of risk aversion.

Appendix A

Detailed results for chapter 2

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 (2.3) to (2.8) found in section 4.3 and the following additional equilibrium conditions (A.1) to (A.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 (A.1) defines the equilibrium condition for inland transport:

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

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 (A.2) gives the equilibrium condition for sea transport between port node p and import node i:

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

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 (2.3) 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:

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

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 (2.8) 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 (A.5). The equilibrium condition for ports does not include a Lagrangian multiplier for maximum investments, as maximum port investments are not constrained. Equations (A.4) and (A.5) define the equilibrium conditions for mine and port capacity investments:

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

and

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

TABLE A.1: Marginal cost data (minimum, maximum and median).

	2005			2030			
in USD_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
U.S. - N. Appalachia	22	50	27	43	97	52	Longwalling
U.S. - Southern Appalachia	22	50	27	42	96	52	Longwalling/Dragline
U.S. - Illinois basin	20	35	43	37	65	47	Room and Pillar/Longwalling
U.S. - N. PRB	5	15	7	9	28	12	Dragline/Truck and Shovel
U.S. - 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 A.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 invest	Shanghai	311.0	0.0	694.9	0.0
QLD UG	QLD - port	7.9	8.4	8.3	8.4	Shaanxi invest	Hong Kong	348.9	0.0	564.8	0.0
NSW OC	NSW - port	40.0	53.6	46.2	58.3	Shaanxi invest	Beijing	0.0	137.6	0.0	220.6
NSW UG	NSW - port	19.8	26.9	23.1	30.0	Shaanxi invest	CH - port	0.0	501.5	0.0	999.5
SA	SA - port	46.4	54.4	33.5	53.1	Xinjiang invest	Shanghai	195.2	0.0	441.9	0.0
IR	IR - port	133.6	171.5	88.5	172.9	Xinjiang invest	Hong Kong	202.6	0.0	312.0	0.0
RU Donezk	RU med -port	24.6	25.3	22.5	25.4	Xinjiang invest	CH - West	0.0	45.6	5.0	355.9
RU Kuzbass	RU pacific - port	1.5	26.7	0.0	44.8	QLD - port	Taiwan	29.0	35.5	35.7	44.4
RU Kuzbass	RU 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	S. 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
U.S. - N. App.	U.S. - N. Atlantic	69.6	69.6	73.7	73.7	NSW - port	India - east	0.0	0.0	25.3	0.0
U.S. - N. App.	U.S. - S. Atlantic	63.1	74.5	86.1	122.6	NSW - port	Chile	9.9	9.9	11.0	0.0
U.S. - S. App.	U.S. - ctrl.	80.8	109.8	121.9	179.5	NSW - port	Hong Kong	0.0	145.4	0.0	150.6
U.S. - S. App.	U.S. - S. Atlantic	86.4	69.5	73.9	30.2	SA - port	NW Europe	82.8	70.2	62.8	0.0
U.S. - S. App.	U.S. port	0.0	0.0	0.0	23.3	SA - port	India - west	2.7	36.1	20.1	53.5
U.S. - Illinois basin	U.S. - ctrl.	128.5	99.5	99.7	21.5	SA - port	India - east	0.0	0.0	0.0	53.5
U.S. - Illinois basin	U.S. - SE ctrl.	0.9	29.9	29.8	108.0	SA - port	Brazil	8.5	8.5	11.1	6.6
U.S. - N. PRB	U.S. - ctrl.	0.0	0.0	0.0	20.7	IR - port	Taiwan	28.0	0.0	0.0	36.2
U.S. - N. PRB	U.S. - NW ctrl.	130.4	130.4	138.1	138.1	IR - port	India - west	23.6	0.0	0.0	0.0
U.S. - N. PRB	U.S. - SW ctrl.	108.1	108.1	98.4	82.1	IR - port	India - east	36.1	36.1	28.3	0.0
U.S. - N. PRB	U.S. - W.	101.7	101.7	107.8	107.8	IR - port	Other Asia	51.1	51.1	65.5	65.5
U.S. - S. PRB	U.S. - SW ctrl.	28.3	28.4	46.1	62.4	IR - port	Hong Kong	0.0	101.8	0.0	88.9
CH - IMAR	Beijing	185.0	210.7	228.4	246.1	RU pacific - port	Japan	0.0	53.1	0.0	0.0
CH - Shanxi	Beijing	163.3	0.0	238.3	0.0	RU pacific - port	S. Korea	5.0	0.0	0.0	87.7
CH - Shanxi	CH - N.	361.3	361.3	343.7	484.1	RU med -port	NW Europe	22.6	2.8	20.6	0.0
CH - Shanxi	CH - port	16.2	244.3	68.5	178.8	RU med -port	Med. Europe	62.1	0.0	61.4	0.0
CH - Shaanxi	Shanghai	132.2	0.0	0.0	0.0	Colombia - port	Med. Europe	0.0	62.1	0.0	53.2
CH - Shaanxi	CH - West	0.0	171.1	177.0	177.0	Colombia - port	NW Europe	0.0	5.4	0.0	66.4
CH - Henan	Shanghai	193.7	201.7	167.0	202.8	Colombia - port	Chile	0.0	0.0	0.0	11.0
CH - Shangdong	CH - N.	0.0	0.0	140.4	0.0	Colombia - port	U.S. - SE ctrl.	74.1	72.1	71.9	0.0
CH - Shangdong	Shanghai	122.5	137.2	0.0	143.6	CH - port	S. Korea	16.2	95.3	68.5	22.9
CH - other	Hong Kong	95.4	318.6	0.0	351.0	CH - port	Shanghai	0.0	607.4	0.0	921.5
CH - other	CH - West	834.6	617.9	936.4	585.4	CH - port	Hong Kong	0.0	43.2	0.0	233.8
Australia invest	NSW - port	138.4	160.0	160.0	160.0	U.S. port	NW Europe	0.0	0.0	0.0	23.3
SA invest	SA - port	47.6	60.5	60.5	60.5	Venezuela - port	NW Europe	0.0	27.0	20.7	14.4
IR invest	IR - port	5.2	17.6	5.2	17.6	Venezuela - port	Med. Europe	0.0	0.0	0.0	8.2
RU invest	RU pacific - port	3.5	26.3	0.0	42.9	Venezuela - port	Brazil	0.0	0.0	0.0	4.5
RU invest	RU med -port	25.1	19.6	28.6	14.9	Venezuela - port	U.S. - SE ctrl.	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
U.S. invest	U.S. - S. 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 A.3: Projected marginal costs of supply in both scenarios.

	2020		2030			2020		2030	
in USD_{2009}/t	by-train	by-wire	by-train	by-wire		by-train	by-wire	by-train	by-wire
QLD OC	50.4	43.9	79.7	56.3	U.S. - ctrl.	77.4	75.5	93.9	86.4
QLD UG	57.8	51.3	87.8	64.4	U.S. - NW ctrl.	60.9	60.8	74.6	69.1
NSW OG	53.4	46.2	81.9	58.3	U.S. - S. atlantic	88.4	86.5	106.5	98.9
NSW UC	53.4	46.2	74.6	58.2	U.S. - SE ctrl.	94.4	92.5	113.2	105.6
SA	50.2	45.4	74.7	59.2	U.S. - SW ctrl.	74.5	74.5	90.1	84.6
IR	53.6	46.7	82.1	61.0	U.S. - Western	46.1	46.1	57.8	52.4
RU Donezk	65.5	60.3	93.8	74.6	Beijing	66.9	63.3	97.0	75.8
RU Kuzbass	45.7	40.5	71.0	51.8	CH - N.	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	CH - West	81.0	71.5	112.4	108.0
U.S. - N. App.	54.7	52.8	68.3	60.7	AI invest	53.4	46.2	81.9	58.3
U.S. - S. App.	57.0	55.1	70.6	63.1	SA invest	50.2	45.4	74.6	59.2
U.S. - Illinois basin	69.2	67.3	84.6	77.1	IR invest	53.6	46.7	82.1	61.0
U.S. - N. PRB	26.8	26.7	35.9	30.5	RU invest	45.7	40.5	71.0	51.8
U.S. - S. PRB	37.3	37.3	47.6	42.1	Colombia invest	63.9	63.0	82.7	74.2
CH - IMAR	44.5	40.9	70.9	49.7	U.S. invest	58.3	56.4	72.1	64.5
CH - Shanxi	56.7	52.9	85.1	63.7	Venezuela invest	60.8	61.9	81.7	71.8
CH - Shaanxi	54.5	45.7	81.5	77.0	Shaanxi/IMAR invest	56.2	83.3	84.6	84.3
CH - Henan	60.8	55.8	89.2	52.0	Xinjiang invest	10.5	33.0	30.2	25.7
CH - Shandong	55.3	50.3	83.1	59.9	QLD - port	64.4	57.9	95.1	71.8
CH - other	68.9	59.4	98.3	93.9	NSW - port	62.2	55.0	91.7	68.1
N.-W. Europe	101.5	96.7	119.8	110.4	SA - port	63.4	58.6	89.7	74.3
Med. Europe	92.9	88.2	121.0	101.8	IR - port	63.3	56.5	93.7	72.7
Japan	89.7	83.4	120.7	97.1	RU baltic - port	82.4	78.4	110.9	91.3
S. Korea	88.2	84.4	121.4	98.1	RU pacific - port	74.0	68.7	103.7	82.4
Taiwan	89.5	83.0	120.3	96.9	RU med - port	72.1	66.9	101.6	82.4
India west	92.9	88.2	116.9	101.8	Colombia - port	68.1	67.3	87.5	79.0
India east	91.2	84.4	117.1	100.6	CH - port	74.2	70.5	105.5	84.2
Brazil	93.8	89.1	117.8	102.7	U.S. - 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
U.S. - N. Atlantic	84.6	82.7	102.2	94.6					

Appendix B

Detailed results for chapter 3

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

	SA	*RU*	*VE*	*VN*	*IR*	*CO*	*PRC*	*U.S.*	*AU*	*PL*	*NW*
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 (2011a), own calculations.

Appendix C

Detailed results for chapter 4

Proof of proposition in section 4.2.2: We consider a setup with a national player A which controls two firms that can produce a single commodity x: F_1 (exporter) and F_2 (domestic supplier). Furthermore, 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 in which 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:

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

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

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 the 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 than 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 an even higher redirection of domestic supply. In this case, domestic supply

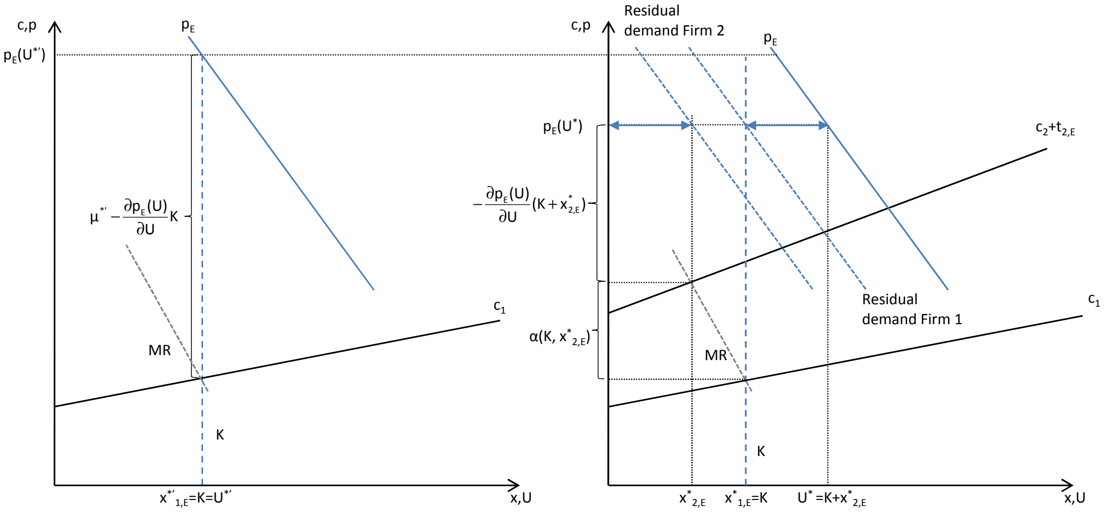

FIGURE C.1: Export market equilibrium for the *export-only setup* (left) vs. *export & domestic setup* (right).

to the export market acts as a backstop for export market prices in the case that we also consider the domestic market. The price bias in a competitive setup would therefore be:

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

Table C.1: Actual and modelled steam coal trade market flows in mt 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

Assumptions for chapter 5

Table D.1: Scenario tree data and stochastic discount factors.

Year	**2009**	**2015**			**2020**					
scenario node		**l**	**m**	**h**	**ll**	**lh**	**ml**	**mh**	**hl**	**hh**
GDP bn $ (2009 PPP)	9449	14602	16019	16287	18636	20480	21436	23536	21796	23932
Intensity (gce/$ PPP)	343	288	288	309	245	245	245	245	262	262
TPED (mtce)	3241	4208	4616	5028	4564	5016	5250	5765	5720	6280
fossil (mtce)	2986	3745	4154	4566	3880	4331	4567	5081	5036	5597
coal (mtce)	2175	2651	3062	3474	2671	3123	3358	3872	3827	4388
non-fossil (mtce)	255	462	462	462	684	684	684	684	684	684
market returns	1.00	0.80	1.25	1.50	0.90	1.30	0.90	1.30	0.90	1.30
Stoch. discount factor	1.00	1.84	0.86	0.31	1.5	0.5	1.5	0.5	1.5	0.5

Table D.2: Supply assumptions.

	a	b	Cap	c^{Inv}	mine life	g	h	Cap^{max}
Shanxi	61.11	0.28	117	189	20	0.05	-0.001	180
Shaanxi	56.45	0.27	106	203	20	0.05	-0.0009	240
Quinhuangdao	82.73	0.09	354	163	20	0.05	-0.0001	650
Other	70.00	0.59	36	224	20	0.05	-0.003	150
Shandong	82.73	0.16	118	178	20	0.05	-0.0005	150
IR	35.71	0.18	203	129	15	0.07	-0.0003	320
QLD	66.67	0.56	50	240	20	0.05	-0.0025	100
NSW	55.56	0.19	86	172	20	0.05	-0.0005	150
VN	40.83	0.45	26	128	20	0.05	0	35
RU east	83.33	0.58	29	172	20	0.05	-0.006	70
RU west	78.36	0.42	62	204	20	0.05	-0.002	90
SA	40.83	0.67	61	222	20	0.05	-0.005	90
CO	27.78	0.50	67	150	20	0.05	-0.004	95
APP1	72.22	0.99	23	200	20	0.05	-0.009	55
APP2	94.44	1.23	23	244	20	0.05	-0.015	70
PL	81.67	2.72	4	210	20	0.05	0	15
VE	50.00	1.00	10	110	20	0.05	-0.01	20

Table D.3: Demand assumptions (Elasticity e, reference demand D_{ref} and reference price p_{ref}).

scenario	s	s	s	l	l	l	m	m	m	h	h	h	ll	ll	ll
demand region	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}
Shandong	-0.3	308	123	-0.3	345	143	-0.2	398	143	-0.3	452	143	-0.3	348	166
Jiangsu	-0.3	232	127	-0.3	261	148	-0.2	301	148	-0.3	342	148	-0.3	263	171
Zhejiang	-0.3	117	127	-0.3	131	148	-0.2	151	148	-0.3	172	148	-0.3	132	171
Guangdong	-0.3	41	134	-0.3	46	155	-0.2	53	155	-0.3	60	155	-0.3	46	180
Fujian	-0.3	58	134	-0.3	65	155	-0.2	75	155	-0.3	86	155	-0.3	66	180
JA	-0.3	119	121	-0.3	124	140	-0.3	124	140	-0.3	124	140	-0.3	130	162
KR	-0.3	76	127	-0.3	80	148	-0.3	80	148	-0.3	80	148	-0.3	84	171
TW	-0.3	48	129	-0.3	50	150	-0.3	50	150	-0.3	50	150	-0.3	53	174
OA	-0.3	34	134	-0.3	45	156	-0.3	45	156	-0.3	45	156	-0.3	51	180
IN-West	-0.3	23	119	-0.3	57	138	-0.3	57	138	-0.3	57	138	-0.3	85	160
IN-East	-0.3	23	119	-0.3	57	138	-0.3	57	138	-0.3	57	138	-0.3	85	160
EU-MED	-0.3	37	107	-0.3	37	124	-0.3	37	124	-0.3	37	124	-0.3	33	144
EU-ARA	-0.3	80	107	-0.3	82	124	-0.3	82	124	-0.3	82	124	-0.3	74	144
EU-East	-0.3	42	107	-0.3	53	124	-0.3	53	124	-0.3	53	124	-0.3	53	144
US	-0.3	13	105	-0.3	3	122	-0.3	3	122	-0.3	3	122	-0.3	3	141
CA	-0.3	2	105	-0.3	1	122	-0.3	1	122	-0.3	1	122	-0.3	1	141
LA	-0.3	16	105	-0.3	19	122	-0.3	19	122	-0.3	19	122	-0.3	21	141

scenario	lh	lh	lh	ml	ml	ml	mh	mh	mh	hl	hl	hl	hh	hh	hh
demand region	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	e	D_{ref}	p_{ref}	elasticity	D_{ref}	p_{ref}
Shandong	-0.3	406	166	-0.3	437	166	-0.3	504	166	-0.2	498	166	-0.3	571	166
Jiangsu	-0.3	307	171	-0.3	330	171	-0.3	381	171	-0.2	376	171	-0.3	432	171
Zhejiang	-0.3	154	171	-0.3	166	171	-0.3	191	171	-0.2	189	171	-0.3	217	171
Guangdong	-0.3	54	180	-0.3	58	180	-0.3	67	180	-0.2	67	180	-0.3	76	180
Fujian	-0.3	77	180	-0.3	83	180	-0.3	95	180	-0.2	94	180	-0.3	108	180
JA	-0.3	130	162	-0.3	130	162	-0.3	130	162	-0.3	130	162	-0.3	130	162
KR	-0.3	84	171	-0.3	84	171	-0.3	84	171	-0.3	84	171	-0.3	84	171
TW	-0.3	53	174	-0.3	53	174	-0.3	53	174	-0.3	53	174	-0.3	53	174
OA	-0.3	51	180	-0.3	51	180	-0.3	51	180	-0.3	51	180	-0.3	51	180
IN-West	-0.3	85	160	-0.3	85	160	-0.3	85	160	-0.3	85	160	-0.3	85	160
IN-East	-0.3	85	160	-0.3	85	160	-0.3	85	160	-0.3	85	160	-0.3	85	160
EU-MED	-0.3	33	144	-0.3	33	144	-0.3	33	144	-0.3	33	144	-0.3	33	144
EU-ARA	-0.3	74	144	-0.3	74	144	-0.3	74	144	-0.3	74	144	-0.3	74	144
EU-East	-0.3	53	144	-0.3	53	144	-0.3	53	144	-0.3	53	144	-0.3	53	144
US	-0.3	3	141	-0.3	3	141	-0.3	3	141	-0.3	3	141	-0.3	3	141
CA	-0.3	1	141	-0.3	1	141	-0.3	1	141	-0.3	1	141	-0.3	1	141
LA	-0.3	21	141	-0.3	21	141	-0.3	21	141	-0.3	21	141	-0.3	21	141

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NON-REFEREED PUBLICATIONS & WORKING PAPERS

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