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by

Moritz Paulus and Johannes Trüby

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Moritz Paulus[a,*], Johannes Trueby[a]

[a] *Institute of Energy Economics, University of Cologne, Vogelsanger Strasse 321, 50827 Cologne, Germany*

Abstract

In this work we demonstrate the effects of different Chinese transport infrastructure investment strategies on long run marginal costs of steam coal supply in Europe. Increasing Chinese demand for steam coal will lead to a growing need for additional domestic infrastructure in China as production hubs and demand centers are spatially separated. If domestic transport capacity is only available at elevated costs, Chinese power generators could turn to the global trade markets and increase steam coal imports. Increased Chinese imports could significantly influence global trade market price levels which would especially affect nations mainly relying on imports, like for example Europe. We analyze the scope of this effect under different assumptions for Chinese transport infrastructure developments. For this purpose, we develop a spatial equilibrium model for the global steam coal market. For our assumption regarding production and transport cost evolutions, we rely on an input factor-based cost calculation methodology. We find out that the investigated Chinese infrastructure decisions have a modest impact on long run marginal costs of supply for Europe and the US but significant effects for China.

Keywords: Steam coal, MCP, non-linear optimization, China, Europe, transport infrastructure

JEL classification: L94, L92, C61, Q30

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1. Introduction

While steam coal sourcing and prices have not been a real problem in the last decades and steam coal market prices have not seen the price spikes observable in natural gas or oil markets in the last decade, this

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[*] Corresponding author

Email addresses: `Moritz.Paulus@uni-koeln.de` (Moritz Paulus), `Johannes.Trueby@uni-koeln.de` (Johannes Trueby)

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situation could change. As the center of gravity and price setting in the global steam coal trade market has shifted to the Asian region since 2005, the Atlantic market region could face challenges regarding its supply costs for steam coal. Important questions in this context are: How does the sourcing of globally traded steam coal change? How will costs of supply change for the Atlantic region? The main driver for these questions is the future evolution in China. Established energy projections show that Chinese demand will rise until 2035 by 80% to 130% compared to 2007 (EIA, 2010b). In order to cover this demand explosion, China faces a plethora of challenges: it has to invest into approximately 2 billion tonnes of steam coal mining capacity until 2030 (not counting for closures of existing mines); it must signifcantly increase its exploration efforts to generate proven, marketable reserves, and, maybe the moste important challenge, it must invest into its already overstrained domestic transport infrastructure to guarantee that the additonal steam coal production reaches the demand centers along the coast.

In this paper, we will focus on the effects which different transport infrastructure investment strategies in China have on the global long run marginal costs of steam coal supply. For this analysis we develop and present a normative bottom-up model which minimizes total costs of global steam coal demand coverage. We design the model as a mixed complementary program by deriving the first order optimality conditions of the associated optimization problem. The model is validated for the reference years 2005 and 2006. Then, we investigate two scenarios for possible future transport infrastructure investment decisions in China: one scenario assumes further investment into railroad transport to transport coal production to the demand centers. The second scenario assumes large-scale investment into HVDC transmission lines which allows mine-mouth coal fired power plants and electricity transmission to the demand centers. We then project steam coal flows and marginal supply cost patterns for for both scenarios up to 2030.

The remainder of the paper is structured into seven sections: after a round-up of relevant literature regarding supply cost modeling and coal market analyses in chapter two we will shortly describe the current situation in the steam coal trade market in chapter three. Then, we introduce our model in chapter four. Chapter five describes the underlying dataset. Chapter six depicts the scenario assumptions and chapter seven reports model results. Chapter eight concludes the paper.

2. Related Literature

The steam coal world markets' most obvious characteristic is its spatial structure. Steam coal demand regions are not necessarily at the location of the coal fields. Coal fields are dispersed widely over the globe and internationally traded coal is usually hauled over long distances to satisfy demand. This spatial structure causes certain implications for the market equilibrium. The economics of such spatial markets have been scrutinized by researchers 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 maximization problem under the assumption of perfect competition. Based on Samuelson's findings Takayama and Judge (1964) develop 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, 1986) 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 generalized problems.

However, published articles on steam coal market analysis have so far been scarce at best. Most of the relevant literature has been centered on analyzing 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 (1984) analyze strategic behavior in international steam coal trade in the early 1980s. In both articles the authors' model is an instance of a mixed complementary problem (MCP), derived by the Karush-Kuhn-Tucker conditions which the modeled market participants face and a series of market clearing conditions. Besides perfect competition they model different imperfect market structures. Firstly, they model South Africa as a monopolist, secondly they examine a duopoly consisting of South Africa and Australia, thirdly, they test for a duopoly with a competitive fringe and Japan as a monopsonist on the demand side. The authors find that the duopoly/monopsony situation simulates the actual trade patterns well 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 analyze the effect on steam coal production volumes and trade flows. 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). They apply their model to measure performance of the domestic US steam coal market. They find out that the US coal market cannot be satisfactorily be described by the spatial Cournot competition. Haftendorn and Holz (2010) developed a model of the steam coal trade market were they model exporting in a first scenario as Cournot players and in a second scenario as competitive players. They follow the same logic as Abbey and Kolstad (1983) by deriving the first-order optimality conditions for all modeled market actors which leads to a non-linear set of equation with a unique solution given that the Lagrangian is convex. They find no evidence that exporting countries exercised market power in the years 2005 and 2006.

3. Structure of the global seaborne steam coal trade

Considerable changes happened in the market for steam coal during recent years. The global seaborne hard coal trade market amounted up to 839 Mt in 2008 an increase of 58% compared to the year 2000. Of global seaborn hard coal trade, the majority is steam coal[1] (639 Mt in 2008). The seaborne trade market can be divided into a pacific market region and an atlantic market region[2].

The pacific market basin saw a large increase not only in domestic production and demand but also in seaward traded volumes (cf table 1). It has been outperforming the Atlantic basin in terms of relative market size growth through the last years. On the supply side, especially Indonesia and Australia managed to significantly increase its exports between 2000 and 2008. The new driving players on the demand side have been the rising economic superpowers: India and especially China .

Table 1: Selected data for steam coal for the pacific basin for 2008 in Mt

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

The Atlantic market region is dominated by three large net exporters, Colombia, Russia and South Africa (cf table 2). The US is a swing supplier in the Atlantic basin and mid to high cost US mines have been the marginal suppliers for Europe during most of 2008. 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 phase out of German coal mines until 2018 and the decline in Polish and British coal production will counter or even overcompensate

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[1] Steam coal are hard coals which are used in electricity geenration. Typically, they are of sub-bituminous, bituminous or even anthracite quality.

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

this effect and will most likely expose Germany, Poland and other Eastern European nations even more to procurements from the world trade market (Ritschel, 2009a; IEA, 2009a).

Table 2: Selected data for steam coal for the Atlantic basin for 2008 in Mt

Country	Production	Consumption	Import	Export	Net-Export
Colombia	77.3	3.7	0.0	73.6	73.6
Russian Federation	181.9	121.9	25.8	85.8	60.0
Republic of 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

4. The Model

We model the global steam coal market as a spatial inter temporal equilibrium model. There are three types of model entities: mine owners, port operators and importers. To each actor we assign nodes representing port facilities, mine regions and import terminals. The nodes are interconnected by arcs representing inland transportation and sea routes. We assume 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 as well as investments into capacity. Transport operators are exogenously modeled and transport cost fees represent tariffs which coal companies have to pay for coal haulage, not marginal costs. These transport fees do not necessarily cover always full costs[3]. Further, we implicitly assume perfect and complete information of all actors regarding demand volumes, production and transport costs and capacities.

Compared to the markets for oil and natural gas, we consider the global steam coal market generally competitively organized and well integrated[4]. We formulate the model as a mixed complementary problem (MCP) by deriving the Karush-Kuhn-Tucker conditions from the original convex optimization problem.

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[3] In some countries like Russia or China for example, freight tariffs are heavily subsidized by the government.

[4] Empirical evidence for steam coal market integration is e.g. 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 in the year 2005 and 2006. However, it has so far not been investigated if single countries which control large state-owned mine

4.1. Notation

In this section we provide a description of the sets, parameters and variables used in the model formulation. The time horizon of the model $T = \{2005, 2006, \ldots, t, \ldots, 2030\}$ includes periods on an annual basis from 2005 until 2015, and time periods in five step intervals from 2015 onwards to 2030. 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 a 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 $i, j \in N$.

The mine production cost C_{mt} is a function of production volume S_{mt} and is modeled 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 α_{mt}, then follows a linear trend with slope β_{mt} until production reaches almost the capacity limit. As soon as the supply level approach production capacity limits the marginal costs can increase exponentially depending on parameter γ_{mt}. 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 fields. These mines have already exploited the largest part of their marketable reserves. 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 curve $c_{mt}^{S,M}$ of C_{mt} is then defined as:

$$c_{mt}(S_{mt}) = \alpha_{mt} + \beta_{mt} \cdot S_{mt} + \gamma_{mt} \ln \left(\frac{Cap_{lt}^{M} + Cap_{lt}^{M,max} - S_{mt}}{Cap_{lt}^{M} + Cap_{lt}^{M,max}} \right), \qquad \alpha_{mt}, \beta_{mt} \geq 0, \gamma_{mt} \leq 0. \tag{1}$$

4.2. Model formulation

We model the spatial equilibrium in the global steam coal market by minimizing the total discounted system costs under a set of restrictions and derive the first-order optimality conditions. This formulation is the dual problem to the welfare maximization problem in spatial markets if we set demand elasticities to zero and restrict that demand has to be satisfied in every period and region (Takayama and Judge, 1964;

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enterprises may exert market power through volumes or through taxes.In the global steam coal market a large number of both, state-run mining enterprises and privately owned companies compete with each other. According to Ritschel (2010), the largest ten internationally operating mining companies together controlled only about one quarter of the global hard coal mining production in 2009. Given the availability of additional reserves and potential mining capacity, the potential for enterprises to exercise market power on the global steam coal market seems currently quite low. Theoretically, the spatial price equilibrium in such a market is fundamentally marginal cost based (Samuelson, 1952).

Table 3: Model parameters

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

Table 4: Model variables

Variable	**Dimension**	**Description**
S_{mt}	Mt	Amount of supply in mine region m in period t
I^M_{mt}	Mtpa	Mine capacity investment in mine region m in period t
I^P_{pt}	Mtpa	Port capacity investment at export harbor p in period t
$T_{a_{(ij)}t}$	Mt	Total transport volume on arc $a_{(ij)}$ in period t
μ_{nt}	M$\$_{2009}$/Mt	marginal costs of supply in node n in period t
λ_{mt}	M$\$_{2009}$/Mt	capacity scarcity rent in mining region m in period t
ϵ_{pt}	M$\$_{2009}$/Mt	capacity scarcity rent for export terminal p in period t

Samuelson, 1952). The resulting equilibrium corresponds to a perfectly competitive market environment with marginal cost-based allocation at each model node $m \in N$, cost-based trade flows and investments in the network. The objective function consists of production, transportation, turnover and investment costs that every producer and port operator minimizes with respect to satisfaction of demand. Producers sell their coal at the export terminals to exporters and traders who ship the coal via bulk carriers on a least cost basis to the demand centers. Turnover costs are interpreted as marginal costs. Costs for transport represent prices and tariffs which are relevant for coal producers and exporters. Note that these transport tariffs not necessarily have to coincide with full costs. In many countries, e.g. Russia and China, transportation tariffs are set by regulatory institutions and are often subsidized. With keeping our mentioned assumptions in mind this corresponds to minimizing the sum of all cost components:

$$
\begin{aligned}
\min_{x \in \Omega} O(x) = & \sum_{t \in T} d_t \Bigg[\sum_{m \in M} \Big(C_{mt}(S_{mt}) \cdot S_{mt} + c^{I,M}_{mt} I^{I,M}_{mt} \Big) \\
& + \sum_{a_{(ij)} \in A} T_{a_{(ij)}t} \cdot c^{T}_{a_{(ij)}t} + \sum_{p \in P} c^{P}_{pt} \left(\sum_{i \in I} T_{a_{(pi)}t} + c^{I,P}_{pt} I^{I,P}_{pt} \right) \Bigg], \qquad (2)
\end{aligned}
$$

with the decision vector $x = (S_{mt}, T_{a_{(ij)}t}, I^{M}_{mt}, I^{P}_{pt})$ and Ω being the set of all feasible solutions. The objective function is strictly convex, as c_{mt} is a strictly convex function for $\gamma < 0$ (which is always the case) and all other cost components are convex in their respecting variables. Ω is defined by a set of model constraints which we will describe now:

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

$$S_{mt} - \sum_{p \in P} T_{a_{(mp)}t} = 0 \qquad (\mu_{mt}) \qquad \forall m, t. \qquad (3)$$

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

$$\sum_{m \in M} T_{a_{(mp)}t} - \sum_{i \in I} T_{a_{(pi)}t} = 0 \qquad (\mu_{pt}) \qquad \forall p, t. \qquad (4)$$

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

$$\sum_{p \in P} T_{a_{(pi)}t} - D_{it} = 0 \qquad (\mu_{it}) \qquad \forall i, t. \qquad (5)$$

Mine production is restricted by mine capacity limits. However, endogenous mine investments are possible from 2010 onwards:

$$S_{mt} - \sum_{t'=2010}^{t} I^{M}_{mt'} - Cap^{M}_{mt} \leq 0, \qquad (\lambda_{mt}) \qquad \forall m, t. \qquad (6)$$

The same holds for port capacities:

$$\sum_{i\in I} T_{a_{(pi)}t} - \sum_{t'=2010}^{t} I^{P}_{pt'} - Cap^{P}_{pt} \leq 0, \qquad (\phi_{pt}) \qquad \forall p, t. \tag{7}$$

Furthermore, mine capacity expansions are limited by geographical, geological and political and economic parameters. While such potentials are hard to estimate, they are necessary to avoid that the most cost efficient mine regions are expanding beyond all realistic bounds. Typical estimates can be derived from expert opinions and market analyses. We base our maximum investment potential on Ritschel (2009b) so that we can restrict:

$$\sum_{t'=2010}^{t} I^{M}_{mt'} - Cap^{M,max}_{mt} \leq 0, \qquad (\epsilon_{mt}) \qquad \forall m, t. \tag{8}$$

The set of all feasible solutions Ω is constrained by the explained set of model constrains. The objective function and the restrictions (3) to (8) form our minimization problem WCM. WCM is convex in all its variables. For a convex minimization problem with a non-empty set of feasible solutions, the first order optimality conditions are necessary and sufficient for deriving the unique solution. The equilibrium conditions are then 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 (9) to (13).

Equation (9) gives the equilibrium condition for inland transport. the Lagrangian multipliers μ_{mt} and μ_{pt} 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 the equilibrium, the difference between μ_{mt} and μ_{pt} are the transport costs for transporting one unit of coal between both nodes (if the transport route exists)

$$\frac{\partial L}{\partial T_{a_{(mp)}t}}: \qquad \mu_{mt} + d_t \cdot c^{T}_{a_{(mp)}t} - \mu_{pt} \geq 0 \perp T_{a_{(mp)}t} \geq 0 \qquad \forall m, p, t. \tag{9}$$

Equation (10) gives the equilibrium condition for sea transport between port node p and import node i. The shadow prices μ_{pt} and μ_{it} differ in the equilibrium by bulk carrier transport rates $c^{T}_{a_{(mp)}t}$, by port turnover costs c^{P}_{pt} and also by the Lagrangian multiplier ϕ_{pt}. ϕ_{pt} represents the value of one additional unit of port turnover capacity at port p. ϕ_{pt} can be interpreted as scarcity rent of constrained port capacity

$$\frac{\partial L}{\partial T_{a_{(pi)}t}}: \qquad \mu_{pt} + d_t \cdot c^{T}_{a_{(mp)}t} + d_t \cdot c^{P}_{pt} + \phi_{pt} - \mu_{it} \geq 0 \perp T_{a_{(pi)}t} \geq 0 \qquad \forall p, i, t. \tag{10}$$

The equilibrium condition for production at mine nodes is given by equation (11). The Lagrangian multiplier λ_{mt} gives the value of one additional unit of production capacity. It is non-zero in the case that the capacity restriction (3) has no slack, e.g. production is at the capacity limits. The shadow price μ_{mt}

is defined by the marginal production costs function c_{mt} (the first-order derivative of the production cost function C_{mt}) plus the λ_{mt}which can be interpreted as the scarcity rent at mine m in period t if the mine is at maximum production.

$$\frac{\partial L}{\partial S_{mt}}: \qquad d_t \cdot c_{mt}(S_{mt}) + \lambda_{mt} - \mu_{mt} \geq 0 \perp S_{mt} \geq 0 \qquad \forall m, t. \tag{11}$$

Equations (12) and (13) define the equilibrium conditions for mine and port capacity investments. In the equilibrium, for the case that $I_{mt}^{M} > 0$, the sum of shadows prices for capacity over mine depreciation time $\sum_{\hat{t}=t}^{\hat{t}+a} \lambda_{m\hat{t}}$ has to be equal to investment cost $d_t \cdot c_{mt}^{I,M}$. In this case ϵ_{mt} is zero as the maximum mine investment potential has still not been reached. ϵ_{mt} represents the shadow price of the maximum mine investment constraint described in equation (8). This equilibrium condition ensures that investment costs are always amortized and allows us to interpret μ_{mt} as the long run marginal costs of mine production including costs for capacity expansions. The same holds for the investment equilibrium conditions for ports (13) but without the Lagrangian multiplier for maximum investments, as maximum port investments are not constrained.

$$\frac{\partial L}{\partial I_{mt}^{M}}: \qquad d_t \cdot c_{mt}^{I,M} + \epsilon_{mt} - \sum_{\hat{t}=t}^{\hat{t}+a} \lambda_{m\hat{t}} \geq 0 \perp I_{mt}^{M} \geq 0 \qquad \forall m, t \tag{12}$$

$$\frac{\partial L}{\partial I_{pt}^{P}}: \qquad d_t \cdot c_{pt}^{I,P} - \sum_{\hat{t}=t}^{\hat{t}+b} \phi_{p\hat{t}} \geq 0 \perp I_{pt}^{P} \geq 0 \qquad \forall p, t \tag{13}$$

Of course, model constraints (3) to (8) also have to hold. The model was programmed in GAMS in the MCP format (for MCP programming with GAMS see also Rutherford (1994)).

5. Database

To fully specify the model equations, data on costs and capacities is required. In the process of data acquisition we relied on a multitude of different and potentially heterogeneous sources. This is due to the very difficult data situation on steam coal market data. While there are some publications on steam coal market data available from public institutions like IEA (2009a); EIA (2010a,b) very useful 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 (2010) 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 as for example Bayer et al.

(2009) and Kopal (2008). Industry yearbooks can provide useful information as it is the case for China (PRC, 2007, 2006). National statistics bureaus and mineral ministries seem to provide high quality information, but reports on hard coal mining industries are at best scarce, with notable exceptions of ABARE (2008) and ABS (2006). Not mentioned are a larger number of coal company annual reports as well as information based on expert interviews. Furthermore, our analysis is based on several extensive research projects of Trueby (2009) and Eichmueller (2010) at the Institute of Energy Economics at the University of Cologne.

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

5.1. Topology

Table 5 gives an overview of all 65 model nodes. *New mine regions* are mine type nodes standing for 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. Each export port can ship coal to each of the import regions. To account for their dominant role in the global steam coal market, domestic markets of China and the USA have been explicitly modeled. Both countries alone constitute around 75% of the global steam coal market. For all other mining regions, we model the export production capacity as a residual of total production capacity less domestic consumption.

Transportation routes exists down the value stream from mining regions to the export terminals and then to the demand centers. Altogether 287 transport routes have been modeled.

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 (if at all) mostly only available for mine mouth costs. Our data on mine mouth costs was obtained through annual reports of coal companies, expert interviews and literature sources as described on page 10. This means that possibly not every single mine has been captured in our data which can lead to distortions if we would model each single mine in the model explicitly. Therefore, We fit the available data of mine mouth cash costs and mine capacity to the marginal cost function described in chapter 4 by ordinary least squares. In this way, we extract the characteristics and the absolute level of the production costs for each mining region.

For our projection of marginal mining costs until 2030 we rely on a cost evolution methodology detailed in Trueby (2009). Basically, the methodology calculates future mining costs by escalating the input factor prices

Table 5: Model topology

New mine regions	Mine region	Export terminals	Import regions
Australia invest	Queensland UG	Queensland	North-western Europe
South Africa invest	Queensland OC	New South Wales	Meditaranean Europe
Indonesia invest	New South Wales OG	South Africa	Japan
Russia invest	New South Wales UC	Indonesia	South Korea
Colombia invest	South Africa OC	Russia baltic	Taiwan
USA invest	South Africa UG	Russia pacific	India west coast
Venezuela invest	Indonesia	Russia med	India east coast
PRC - west invest	Russia Donezk	Colombia	USA - North atlantic
PRC - east invest	Russia Kutbazk	China	USA - South atlantic
	Colombia	USA east coast	USA - SE central
	China - Shaanxi	Venezuela	USA - SW central
	China - Shanxi	Vietnam	USA - Central
	China - Shandong		USA - NW central
	China - Henan		USA - Western
	China - IMAR		Other Asia
	China - other		Brazil
	USA - Northern Appalachia		Chile
	USA - Southern Appalachia		Beijing
	USA - Ilinois basin		Shanghai
	USA - Northern PRB		Hong Kong
	USA - Southern PRB		China - West
	Venezuela		China - North
	Viet Nam		

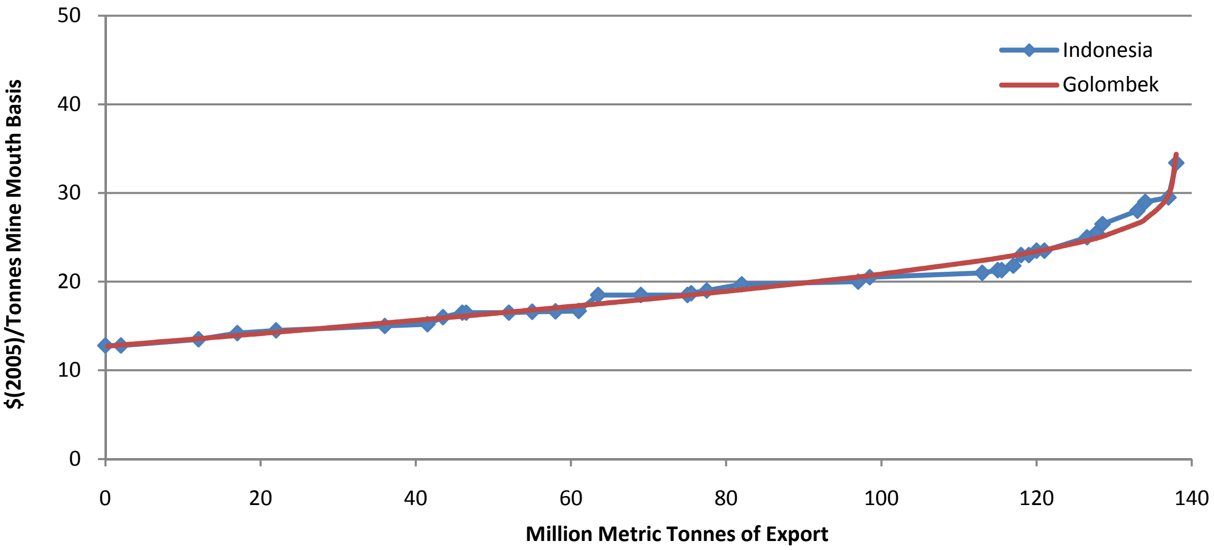

Figure 1: Example of Mine-mouth cash costs curves for existing mines in Indonesia and approximation by marginal cost functions for the year 2005

Table 6: Input factors by relative importance for coal mining production costs in 2005

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

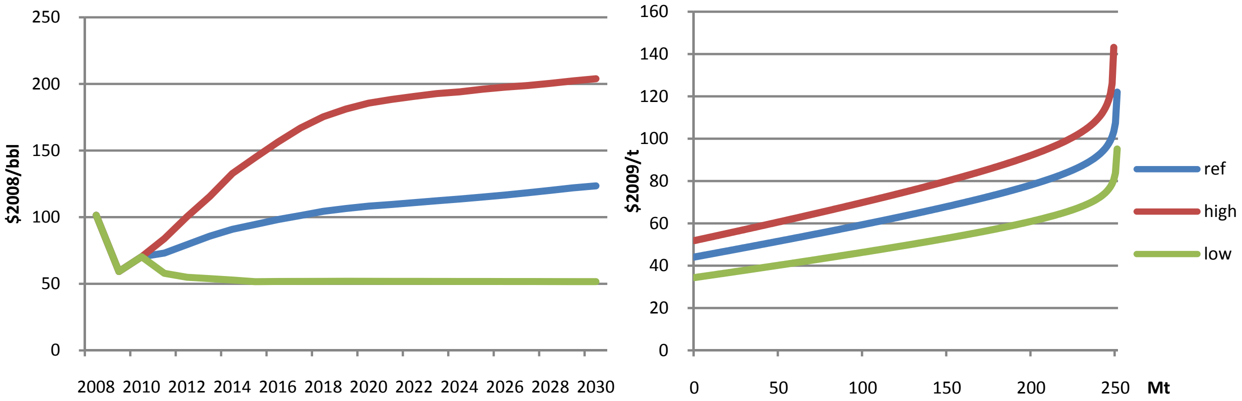

Figure 2: Influence of different oil price projections (left) on the marginal mining costs In Indonesia in 2030 (right)

for mining in accordance to their relative importance in the production process. The relative importance of input factors is derived on a number of sources, for Australia ABS (2006) delivers detailed information, Meister (2008) and Baruya (2007) compare different input factor structures on the global scale. Table 6 gives an overview of the relevance of different input factors on mine production costs in 2005. In underground mining mostly longwalling and room&pillar technologies are applied. Open cast mining sees dragline and truck&shovel operations. For a more detailed description of mining technologies refer to Schiffer and Ritschel (2007) or BGR (2008).

Many of the relevant input factor prices for mining, like explosives, chemicals, and diesel are correlated to the evolution of the oil price. This is obvious as the main production inputs for explosives (in this case ANFOs: Ammonium Nitrite Fuel Oil), chemicals and diesel used in coal mining is oil. We therefore also assume a high correlation of these input factor prices with the oil price for the future. In our scenario analysis we use 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. In figure 2 we demonstrate how the oil price projections of the EIA for the 'high'- 'reference' and 'low' oil price case influence marginal mine production costs for Indonesia in the year 2030. Further assumptions were made on the evolution of prices for the other input factors like tires, electricity, machinery parts and steel mill products.

5.3. Costs for transport, turnover and investments

Inland transportation costs depend strongly on the vehicles used. The three most important transport modes are railway, trucks and river barges in descending order. Selection of transport modes depends greatly on local conditions: Indonesia for example utilizes its network of navigable rivers on Kalimantan to transport most of its coal production with river barges to the export terminals. In countries like China, Australia or Russia, railways carry the bulk of the coal transport. Information on transportation modes and costs of domestic transport is based on Minchener (2004, 2007); Ritschel (2010) and Eichmueller (2010).

To get estimates for the evolution of future domestic transportation costs we follow a similar methodology as done for mining production costs. We inflate inland transportation costs with the estimated impact of diesel and electricity prices on inland transportation per country. We estimated the relative impact of diesel and electricity by the relative importance of truck haulage and railway haulage for the main transport routes. Truck haulage and barge haulage would mean a complete dependence on diesel prices while railway haulage would mean at least a mix between diesel and electricity.

Table 7: Mine and port investment costs

Port	$_(2009)/tpa	Mine region	$_(2009)/tpa
Queensland	16	Australia Invest	39
New South Wales	16	South Africa Invest	33
South Africa	12	Indonesia Invest	43
Indonesia	17	Russia Invest	36
Russia Baltic	21	Colombia Invest	69
Russia pacific	21	USA Invest	27
Russia med	21	Venezuela Invest	69
Colombia	24	China - West Invest	43
China	20	China - east Invest	54
USA East Coast	29		
Venezuela	24		
Viet Nam	17		

A detailed overview of historical seaborne freight costs and projections until 2020 can be found in Trueby (2009). Increases are based on assumptions about future evolution of bunker fuel prices, as well as shipyard capacities, insurance costs and steel costs.

Data on investment costs has been derived from analyzing company reports, business plans, announcements of public institutions like New South Wales' ABARE (2008) and IEA (2003) and also personal communication with experts. This also holds true for port investment costs. Table 7 gives an overview of all used investment costs.

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Table 8: Demand figures for 2005 and 2006 and demand projections until 2030.

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

5.4. Demand

For the necessary demand projections up to 2030 we use the hard coal demand growth projections of EIA (2010b). The growth projections were taken from the *reference case*. We assume that steam coal imports grow in the same rate as domestic demand for the demand regions. demand figures shown in table 8 are absolute demand figures for China and the US. For the other demand regions these figures have to be interpreted as import demand.

6. Scenario setup

Future amounts of Chinese imports have a strong influence on marginal costs of supply in Europe. If Chinese import demand grows, higher volumes have to be procured on the steam coal trade market. This expansion of demand on the trade market leads to more production and mines with higher costs become price setting. The slope of the global steam coal supply functions determines how high the increase in marginal costs is.

Main drivers for future imports into China are steam coal supply and demand. While many experts agree that coal demand in China will be fueled by high economic growth in the future (IEA, 2009b; EIA, 2010b), projected coal demand growth rates vary widely. In this analysis, we will use the coal demand growth projections found in chapter 5 which associates an increase in steam coal demand in China of 2 billion tonnes until 2030.

China has the second largest amount of bituminous and anthracite coals in the world after the US (BP, 2010). Most of the hard coal reserves are located in central China, in the provinces Shanxi, Shaanxi and in the Autonomous Republic of Inner Mongolia (IMAR). There are also other coal bearing areas, as for example in the west of China, in the province Xinjiang. The coal fields in the central provinces as well as in the south and in the east of China have already been developed and are extensively mined. While the mining capacity limits can still be further extended, most of the mines are already operating deep underground at elevated cost levels. 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.

One important hindrance why these lucrative reserves have not been developed so far is the lack of large scale transport infrastructure between the demand hubs on the coast and the eastern regions. Coal transport in China mainly takes place by railway, river barges and coastal shipping. So far, mine-mouth coal-fired power plants in combination with large scale HVDC lines which transport electricity to the coastal demand centers are scarce but are increasingly in the focus of Chinese grid planning authorities (Yinbiao, 2004; Qingyun, 2005).

The projected massive growth in steam coal demand of 2 billion tonnes until 2030 will have to be transported from the main production regions in the center and in the west of China to the coastal demand hubs. In our analysis, we will investigate two scenarios with different assumptions on the transport investments taking place in China to deliver coal-based energy to the demand hubs.

6.1. Scenario 'coal-by-train'

In the first scenario called 'coal-by-train' we assume that China will rely on railways to transport the additional coal production from the coal bearing regions to the consumption areas. This will require massive amounts of investments into railway traces, engines, rolling stock and into the railway electricity grid. The main investments into transport capacity will take place from the central coal bearing regions to Hong Kong and Shanghai (cf. figure 3). Further investments will take place between the western coal fields and the central provinces. Furthermore, variable transportation costs are high: transporting a tonne of steam coal from Shanxi province to Qinhuangdao has cost approximately 6 $/t (PRC, 2010) in 2005. Transporting one tonne of coal from Shanxi to Hong Kong has cost about 36 $/t by railway, which basically doubled the costs of coal. Also, railway transportation costs are likely to increase over time if diesel and electricity prices rise.

6.2. Scenario 'coal-by-wire'

In the second scenario called 'coal-by-wire' we assume that for the additional mine capacity built until 2030 China will build mine-mouth coal fired power plants in combination with HVDC (high voltage direct current) lines which transport the electricity to the demand centers located at the coast. The benefit of this approach is that the variable costs for transporting electricity via HVDC lines are zero. However, electricity losses apply which are up to 3 % depending on the distances (Bahrmann and Johnson (2007)). The HVDC lines are assumed to connect the central coal bearing regions with the coastal centres around Hong Kong and Shanghai. The western areas are not suited for HVDC line connection as they are arid, almost desert-like

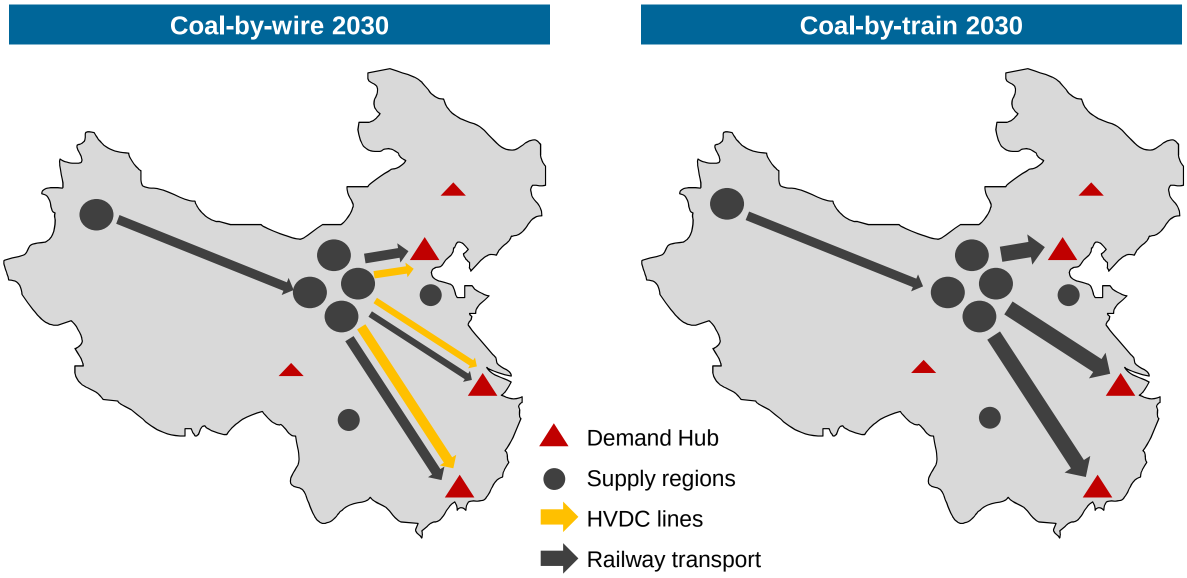

Figure 3: Topology of the scenario setup for China

regions. Therefore, it is unlikely that enough water for the cooling circuits of large-scale coal fired generation capacity will be available there. Coal from western provinces will be transported via railway to the central coal bearing areas where they will fuel coal-fired electricity generation in combination with HVDC lines to the demand centers. As we only model the coal market, all numbers on coal flows from the mining regions *China - west invest* and *China - east invest* to the demand regions have to be understood as electricity equivalents, as the respective coal flows are burnt in mine-mouth coal-fired power plants which transport the generated electricity via HVDC lines to the demand hubs.

6.3. Scenario parameters

Two parameters change between both scenarios: Firstly, transportation costs on the selected transport routes change as HVDC lines operate with zero transport costs. This does not reflect full costs of operation of the HVDC lines, as costs are allocated typically to electricity consumers. We will come to cost efficiency of HVDC line investments in chapter 7.5. Secondly, We have to account for transmission losses generated by the HVDC lines. Table 9 shows how transport costs differ between both scenarios.

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

Table 9: Parameter settings for domestic steam coal transport costs in both scenarios

		2005		2030	
in $\$_{2009}$/t		coal-by-wire	coal-by-train	coal-by-wire	coal-by-train
costs from Shanxi to:					
	Hong Kong	26	26	0	44
	Shanghai	36	36	0	61
	Beijing	6	6	0	11
costs from Shaanxi to:					
	Hong Kong	31	31	0	60
	Shanghai	23	23	0	44
	Beijing	18	18	0	36
costs from IMAR to:					
	Hong Kong	43	43	0	69
	Shanghai	31	31	0	51
	Beijing	11	11	0	18
costs from Xinjiang to:					
	Hong Kong	65	65	49	99
	Shanghai	60	60	49	90
	Beijing	57	57	49	86

7. Results

In this chapter we will outline main model results for the two analyzed scenarios 'coal-by-train' and 'coal-by-wire'. We will validate the model for the base years 2005 and 2006 and then depict marginal costs, trade flows, utilization and welfare effects in the scenario runs for 2020 and 2030.

7.1. Coal Supply in China

Table 10 shows how Chinese coal demand is covered in both scenarios until the model year 2030. The results for the years 2005 and 2006 show, that the model is fairly accurately calibrated an can reproduce the historic production mix. However, reference figures are production volumes and therefore it is not possible to validate domestic trade flows between different Chinese regions.

In the 'coal-by-train' scenario, the main coal suppliers are the central Chinese provinces Shanxi, Shaanxi and IMAR in 2030. They supply 2050 Mt via land transport (mostly railway). A further part of their production is transported to the norther export terminals of Qinhuangdao and shipped via handy size bulk vessels or coastal barges to the Shanghai and Hong Kong regions. This is depicted in table 10 in the category 'reimports'. Western coalfields supply roughly 350 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.

Most importantly, imports play a significant role in the 'coal-by-train' scenario, amounting up to 277 Mt. While this seems to be a fairly small volume compared to overall Chinese demand of more than 4 billion

Table 10: Steam coal market in China by origin

	2005		2006		2020		2030	
	Reference[a]	Model	Reference	Model	by-wire	by-train	by-wire	by-train
China - Shaanxi	154.4	143.8	184.9	149.5	141.6	177.0	176.9	177.0
China - Shanxi	260.1	216.2	280.4	274.9	441.8	202.1	452.8	238.9
China - Shandong	125.1	116.7	125.5	121.3	128.4	143.6	139.2	143.6
China - Henan	176.0	164.8	183.2	171.3	197.9	202.8	201.7	202.8
China - IMAR	165.3	196.2	192.1	207.7	243.3	245.6	245.9	246.1
China - Other	771.5	760.9	779.6	791.0	934.0	936.4	936.4	936.4
China -Reimports	n/a	143.4	n/a	159.1	0.0	323.5	0.0	423.5
China - East Invest	0.0	0.0	0.0	0.0	639.1	476.1	1220.1	1185.0
China - West Invest	0.0	0.0	0.0	0.0	385.3	168.6	813.4	355.9
Indonesia	13.0	2.7	13.4	26.1	0.0	151.6	0.0	87.3
South Africa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6
Australia	2.3	0.0	5.1	0.0	0.0	72.1	0.0	162.2
Viet Nam	11.5	17.9	22.1	29.1	12.8	24.9	0.0	24.9

[a] Values for Chinese provinces for 2005 and 2006 are based on PRC (2008, 2007) and have to be interpreted as production volumes. Therefore, no data is available on reimports for the base year. Import figures are based on IEA data.

tonnes in 2030, it makes up more than 36% of the seaward traded steam coal market. Main importers into China are Australian mines with 162.2 Mt and Indonesian mines with 87.3 Mt. Indonesian mines experience significant cost increases until 2030 because of rising production costs. This is mainly caused by rising diesel prices and deteriorating geological conditions of coal deposits and qualities. As Indonesian mining operations are mostly open-cast truck & shovel operations and therefore are strongly exposed to oil price increases. Due to this 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 reduce transportation costs for the western provinces and therefore incentivize investments. Therefore, the scenario results show a strong increase in mining capacity in the west as the mining costs in this region are fairly low, lying in the range of 11 to 22 $\$_{2009}$/t. With the reduced transport cost burden these mines belong to the cheapest suppliers in China in the scenario 'coal-by-wire' in 2030. Reimports do not play a role as inland transportation of coal based electricity is far more cost competitive as coastal shipping. Imports from foreign countries is completely replaced by cheap domestic production. In this scenario, China is even able to export 74.1 Mt.

7.2. Coal Supply in Europe

The mix of steam coal imports into Europe for the base years, 2020 and 2030 is shown in table 11. The model reproduces a fairly accurate supply mix for Europe in the years 2005 and 2006. Notably, volumes sourced from Latin America are higher than in the reference data and supply is less diversified. Besides statistical errors and differences in energy-mass conversions, coal quality is a factor which may let model results deviate from real trade patterns. In Europe, especially in Germany, 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 for 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 modeled and beyond the scope of this analysis.

In the 'coal-by-train' scenario, the most important supplier for Europe volume-wise is Colombia with more than 64 Mt in 2030. After Colombia, the US supply 52.7 Mt from their Appalachian mines to European ports. Venezuela and Russia both export approximately 25 Mt to Europe. Notably, South African volumes re missing in the European import mix in 2030. In this scenario, South African exports are completely redirected from Europe to the pacific basin. There, they cover Indian import demand substituting Indonesian volumes. The gap that this shift in South African volumes produces in the European supply mix is covered by the high cost US volumes from the Appalachian regions. These high cost US mines therefore are the marginal suppliers to Europe in 2030. While Russia and Latin America can provide steam coal at lower costs, their production capacity and mine investments are already at maximum. Russian production is mostly directed to its pacific ports to cover Japanese and Korean import demand and Latin American mining regions are already providing their maximum production volumes to Europe. Therefore, the last remaining spare capacities are the high-cost underground mines in the Appalachian region. Other domestic coal fields like the Powder River Basin face very high domestic transport costs to the export terminal. Additionally, they often feed mine-mouth coal-fired power generation which reduces their potential to market volumes in the global seaborne trade market.

In the 'coal-by-wire' scenario, the European import mix changes. The higher amount of Chinese production reduces reduces imports and frees large volumes of the steam coal trade market in the pacific basin. Most importantly, Russian and South African volumes are now switching back to the Atlantic basin where they crowd out high cost production volumes. The highest cost mines in the Atlantic basin are the US Appalachian mines, whose production significantly declines from 453 Mt in the 'coal-by-train' scenario to 360

Table 11: Steam coal market in Europe by origin

	2005		2006		2020		2030	
in Mt	Reference[a]	Model	Reference	Model	by-wire	by-train	by-wire	by-train
South Africa	57.5	59.1	62.4	57.1	90.5	37.3	77.1	0.0
Russia	34.5	33.7	38.9	34.9	67.9	62.1	67.9	25.4
Colombia	28.5	47.3	33.6	45.6	0.0	41.1	0.0	64.2
USA	2.8	8.2	3.4	9.0	0.0	0.0	0.0	52.7
Venezuela	1.1	0.0	1.1	9.6	9.1	27.0	20.5	23.1
Indonesia	15.7	11.7	20.5	19.9	0.0	0.0	0.0	0.0
Australia	8.8	8.2	7.0	4.5	0.0	0.0	0.0	0.0
Other	28.7	0.0	28.5	0.0	0.0	0.0	0.0	0.0

[a] The reference data for the years 2005 and 2006 stem from IEA (2008). Note that deviations do not sum up to zero as model results are standardized energy-mass units (25,120 MJ per tonne) while IEA data is in metric tonnes.

Mt in the 'coal-by-wire' scenario. This decline in US steam coal production leads to a different allocation of volumes in the Atlantic basin. Russian exports to Europe increase from 51.6 Mt to 67.9 Mt. South African volumes switch almost completely back to the Atlantic basin with Europe being the recipient of 77.1 Mt. Latin American volumes which formerly covered European import demand are now redirected to the US import terminals on the gulf coast, where they crowd out high cost US mines.

7.3. Long run marginal costs of steam coal supply

With the different allocation of volumes in the Atlantic basin in the 'coal-by-wire' scenario, the marginal costs of supply also change. Obviously, as more cheaper volumes are available, high cost suppliers are pushed out of the market and the marginal costs of supply to each import regions decline.

Table 12 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 strictly monotone over time in China and Europe in both scenarios. Secondly, the LRMC are different in the two scenarios, with the 'coal-by-train' scenario 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 as defined in section 5.4. The increase in input prices are mainly linked to the assumptions made on the oil price evolution (see also page 11). Mining production technology is strongly linked to a number of price-wise highly volatile commodities which often are strongly oil price dependent in their production themselves. This leads to coal mining costs which are closely correlated with oil price evolutions. The increase in demand leads to increasing investment into mine capacity and a higher utilization of existing mines. Both drivers have a cost-raising effect, as investments have to be refinanced and the higher utilization of mines or utilization of so far extra-marginal mines raises marginal production

Table 12: Evolution of long run marginal costs of supply for steam coal in Europe, USA and China

	2005		2006		2020		2030	
in $\$_{(2009)}$/t	Reference[a]	Model	Reference	Model	by-wire	by-train	by-wire	by-train
Beijing	52	51	50	54	66	69	75	90
Shanghai	62	60	58	63	99	119	112	150
Hong Kong	62	60	58	63	99	120	112	155
PRC - West	n/a	53	n/a	56	73	91	96	119
PRC - North	n/a	40	n/a	44	84	87	96	111
North-Western Europe	69	67	69	67	100	104	111	123
Meditaranean Europe	73	66	69	67	91	103	102	124
USA - North Atlantic	47	54	51	54	84	87	95	105
USA - South Atlantic	47	51	51	52	77	80	87	97
USA - SE Central	47	55	51	56	61	63	69	78
USA - SW Central	47	51	51	52	88	91	99	110
USA - Central	47	54	51	54	94	97	106	116
USA - NW Central	47	43	51	42	74	76	85	93
USA - Western	47	34	51	32	46	48	52	61

[a] The reference data for the years 2005 and 2006 stem from IEA (2009a). 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 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 standardized energy-mass units (25,120 MJ per tonne) while IEA data is in metric tonnes.

costs.

The lower LRMC in Europe, the US and especially China in the scenario 'coal-by-wire' in 2030 are caused by the additional approximately 450 Mt Chinese mine capacity which is opened up in the western provinces. This mine capacity becomes highly cost competitive through the installation of HVDC lines within China which reduce transport costs of steam coal. However, the gap of LRMC between both scenarios is different for China and for Europe: The marginal cost supplier for Europe in this scenario changes from the US to Russia. Russian mines are operating in a very broad cost range between 27 and 91 $\$_{2009}$/t in 2030. However, long railway haulage distances to the export terminals in the black sea, the Baltic states or Murmansk significantly increase costs of supply. Therefore, the difference in marginal costs of supply to Europe of Appalachian Mines and the different Russian mines is not that large. The LRMC delta of approximately 10% to 20% shown in table 12 can be basically interpreted as the delta of LRMC of supply to Europe between the US Appalachian mines and Russian mines.

The situation for China is however different. Here, the marginal supplier changes from high-cost Indonesian mines to lower-cost domestic Chinese mines. The LRMC of supply delta between those two suppliers is significant and in the range of 38 $\$_{2009}$/t to 43 $\$_{2009}$/t in 2030. As mentioned previously, while Indonesian mines are highly cost competitive today, the degradation of reserve quality and geological conditions as well as the highly diesel-dependent truck & shovel operation increase marginal mining costs dramatically until

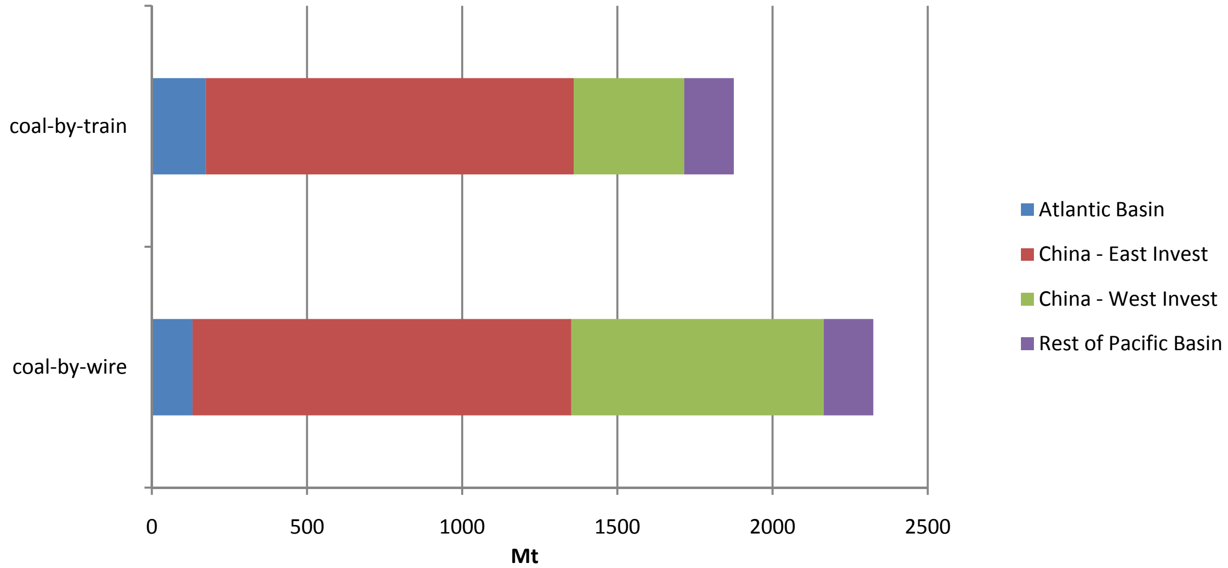

Figure 4: Cumulated mine investments in million tonnes per year in the global steam coal market until 2030

2030.

7.4. Investment and utilization of mines

Figure 4 shows the cumulated mine investments for both scenarios until 2030. Mine capacity additions in the 'coal-by-train' scenario amount up to 1875 Mtpa and in the 'coal-by-wire' scenario up to 2326 Mtpa. The difference in mine investments between both scenarios is largely explained by the higher investments in Western China. Investments into mine capacity in the West of China are by about 457 Mt higher in the 'coal-by-wire' scenario. This is caused by reductions in transportation costs which reduce overall costs of supply from these western mines to the Chinese demand centers, thereby increasing incentives for mine investments in remote regions.

The large difference in mine investments of almost 0.5 bn tonnes of capacity leads to a different utilization of existing mine capacity. In the 'coal-by-wire' scenario existing high-costs mines have a lower production output as the new, cheaper Chinese capacity coming on line crowds them partly out. Table 13 shows mine utilization levels for Chinese and US mine regions for both scenarios. Main differences in mine utilization can be found in the Appalachian regions, the Southern Powder River Basin and the Chinese province of Shanxi. In the US, the Appalachian mines are supply-wise the most expensive capacities available. Therefore, in the 'coal-by-wire' scenario in 2030, about 90 Mt of their production is pushed out of the market , as cheaper South African and Russian volumes are redirected to the Atlantic basin. The Southern Powder River basin region faces higher production costs as the Northern PRB. High transport costs to the demand centers and

Table 13: Utilization levels of US and Chinese mines

	2020		2030	
in [%]	coal-by-wire	coal-by-train	coal-by-wire	coal-by-train
USA - Northern Appalachia	60	68	69	89
USA - Southern Appalachia	67	75	76	94
USA - Illinois basin	100	100	100	100
USA - Northern PRB	97	98	98	100
USA - Southern PRB	39	58	64	92
China - Shaanxi	80	100	100	100
China - Shanxi	67	79	79	100
China - Shangdong	89	100	97	100
China - Henan	98	100	99	100
China - IMAR	99	100	100	100
China - other	100	100	100	100

to the export harbors decrease international competitiveness of this mining region which leads to a certain outcrowding of their production in the 'coal-by-wire' scenario.

In China, especially the high costs mines in Shanxi province experience a decrease of utilization levels. 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 output of Shanxi mines by 136 Mt in the scenario 'coal-by-wire'.

7.5. Welfare effects

Lower worldwide marginal costs in the 'coal-by-wire' scenario lead to welfare effects and change of the spatial distribution of rents (cf. figure 5). In total, welfare effects are positive and amount up to 998 billion $\$_{2009}$. However, allocation of welfare changes: in the 'coal-by-wire' scenario, producer rents in the world besides China are dropping by 462 billion $\$_{2009}$. This is mainly caused by lower global marginal cost levels, as well as lower utilization of high cost US mines which cuts into producer surpluses. Producer rents for China decrease in the scenario 'coal-by-wire', as the lower prices reduce rents and investment costs are higher due to the increased mine capacities in central and western China. If argued from the other side, producers outside China profit from high prices levels and the Chinese need for imports in the 'coal-by-train' scenario.

Consumers profit on a global scale in the 'coal-by-wire' scenario. The difference in consumer rent makes up 1510 billion $\$_{2009}$ cumulated over the model horizon. The largest part of this increase is allocated to China, as the difference in marginal costs of supply between both scenarios is the largest there.

Welfare benefits between both scenarios have to be compared to additional transport infrastructure investments in China. As transport infrastructure investments are not part of the modeled system, cost efficiency has to be proven ex-post. Additional infrastructure for transporting coal from the mines to the

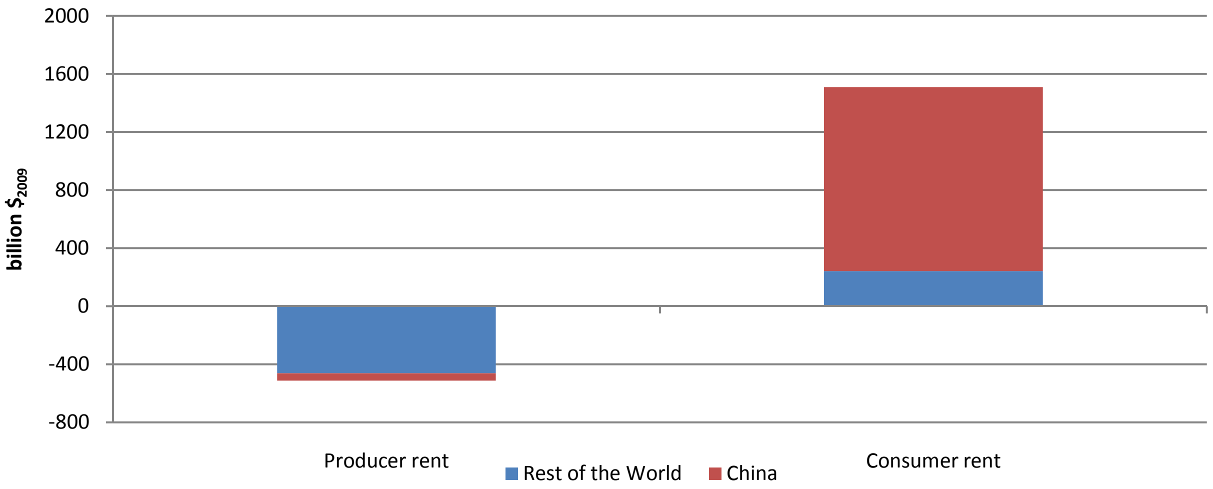

Figure 5: Welfare effects between both scenarios (horizontal axis represents the scenario 'coal-by-train')

demand hubs is needed in both scenarios, however, investment costs for HVDC lines and railways are different. Transport volumes do also change between both scenarios, as investments into mine capacity in China are lower in the 'coal-by-train' scenario. Table 14 gives an aggregated cost efficiency analysis of the additional costs and also cost savings in the 'coal-by-wire' scenario compared to 'coal-by-train'. The higher amounts of coal exploited in Xinjiang province first have to be transported by railway to the central regions in the province of Shaanxi. This leads to extra costs for additional railway infrastructure of 99.4 bn $\$_{2009}$ cumulated up to 2030. The additional HVDC grid which interconnects the new-built mine mouth coal-fired power plants in central China with the coastal demand regions amount up to 779.5 bn $\$_{2009}$ until 2030[5]. However, investment costs into railway infrastructure of 589.8 bn $\$_{2009}$ are avoided compared to the scenario 'coal-by-train'. Total additional costs in the transportation sector including all effects are 189.7 bn $\$_{2009}$.

Compared to the welfare effects in figure 5, the cost analysis shows that investment into HVDC infrastructure is overall cost efficient. Total net welfare surplus accounting for additional transport infrastructure costs is 808 bn $\$_{2009}$ compared to the scenario 'coal-by-train'. While the investment figures seem to be extremely high, one has to keep in mind that we assume that China is facing an increase of steam coal demand of 2 billion tonnes until 2030. This would mean an increase of roughly 40% of the current global demand which only takes place in China.

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[5] We assume that new-built coal-fired power plants in China realize 6800 full load hours on average and efficiency levels of 43%

Table 14: Cost effects in the transport sector in the scenario 'coal-by-wire' compared to scenario 'coal-by-train'.

		Distance	Capital costs railway	Capital costs HVDC	Cost delta 'coal-by-wire'[a] Additional Costs HVDC & railway	Cost savings railway	Total
		km	$\$_{2009}$/tpa	$\$_{2009}$/kW	billion $\$_{2009}$		
Xinjiang to:	Shaanxi	1300	217	-	99.4	0.0	**99.4**
Shaanxi to:	Beijing	1150	192	637	16.6	-11.5	**5.1**
	China Central	1950	325	962	47.2	-36.7	**10.5**
	Shanghai	1450	242	759	351.8	-257.,7	**94.1**
	Hong Kong	2000	333	982	362.7	-283.1	**79.6**
	China West	1000	167	576	1.2	-0.8	**0.4**
Total in billion $\$_{2009}$					**878.9**	**-589.8**	**189.7**

[a] 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. We assume a +800 kV Bipole DC configuration with maximum transmission losses of up to 3.43% at full load depending on transmission distance.

8. Conclusions

In this paper we analyze the influence of Chinese transport infrastructure investment on the LRMC of supply for steam coal in Europe until 2030. We present a normative spatial equilibrium model which minimizes total cost of global demand coverage. The model includes domestic markets for China and the US as well as the main importers and exporters. Proxys for future marginal costs of supply and transport costs are based on a rigid cost structure decomposition which allows us to deduct future supply costs and transport costs estimates for the future based on assumptions of input price evolutions. We then analyze two scenarios with different assumptions on future Chinese infrastructure investment policy. In one scenario, the railway system is massively expanded to accommodate future steam coal demand increase. In the other scenario, an HVDC grid is installed with new coal-fired power stations located next to the coal pits and thus reducing variable costs of transportation.

Our model results show that such infrastructure decisions yield a moderate change to LRMC of supply for steam coal in Europe of up to 10% to 15% by 2030. While steam coal flows and marginal suppliers for Europe change between both scenarios, basically one high-cost supplier (USA) is exchanged for another one (Russia). The Difference in LRMC for Europe between both scenarios reflects the delta of marginal costs of supply to Europe between Russia and the US. LRMC for China change more significantly by up to 38% 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 South Africa and Indonesia. LRMC are then determined by lower cost Chinese mines which subsitute high cost Indonesian mines as the marginal supplier. Thus, a large-scale HVDC grid would not only allow China to be still independent from foreign coal imports by 2030, but also stabilize marginal costs of supply. Welfare effects through investments into HVDC infrastructure are clearly positive even if the difference in transport investment costs for HVDC lines is taken into account. Nevertheless, the transport investment cost estimates outlined for both scenarios show that China is facing a challenge of enormous proportions in terms of financing and coordination to cover its growing energy demand.

Of course, these model results are prone to assumptions we have taken: The results for the LRMC for Europe depend strongly on the amount of US coal available from the Appalachian regions in 2030. As Hook and Aleklett (2009) and Hook and Aleklett (2010) state, recent history shows that productivity is declining rapidly in those regions as the best deposits have been almost exploited. Furthermore, US policy regarding carbon emissions as well as environmental concerns could put US coal mining into a different position in the future. As European costs of supply are based on Appalachian coal in the scenario 'coal-by-train', an increase in US production costs or a tightening of US volumes would change model results significantly, and would probably increase marginal costs of supply for Europe.

Furthermore, we assume that transportation capacity, regardless if it is railway or if it is HVDC transmission, is available on time. We do not model what would happen if transport bottlenecks arise in China when railways are not expanded on time due to lack of national transport infrastructure planning. This point is especially important, as transport infrastructure projects typically have long lead times of several years. In the case of domestic transport bottlenecks, China would have to acquire even larger amounts of steam coal on the international trade market, which would lead to significantly higher marginal costs in the Pacific and the Atlantic basin due to the relative size of Chinese domestic demand compared to the trade market volume.

An important aspect is that, under the assumptions made, China may still be able to cover its steam coal demand by own production in 2030. But this would mean a drastic change in Chinese energy politics: As for example mentioned in MIT (2007), China's national bureaucratic 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 investment projects are divided into many different departments. The weakness of central Chinese institutions promotes that currently decisions regarding the energy system in China are often taken on the grass-roots level. On the local scale, utility companies, governments and other private companies define the scope of energy-related decisions. To give such a large-scale national infrastructure investment project any chance of realization, the national government would have to cut into this well-established webs of local decision makers and form a national energy planning institution which yields enough executive power to bring local agencies into line.

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