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

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Abstract

This paper demonstrates the ways in which different Chinese bulk energy transport strategies affect the future steam coal market in China and in the rest of the world. An increase in Chinese demand for steam coal will lead to a growing need for additional domestic infrastructure as production hubs and demand centers are spatially separated, and domestic transport costs could influence the future Chinese steam coal supply mix. If domestic transport capacity is available only at elevated costs, Chinese power generators could turn to the global trade markets and further increase steam coal imports. Increased Chinese imports could then yield significant changes in steam coal market economics on a global scale. This effect is analyzed in China, where coal is mainly transported by railway, and in another setting where coal energy is transported as electricity. For this purpose, a spatial equilibrium model for the global steam coal market has been developed. One major finding is that if coal is converted into electricity early in the supply chain, worldwide marginal costs of supply are lower than if coal is transported via railway. Furthermore, China's dependence on international imports is significantly reduced in this context. Allocation of welfare changes particularly in favor of Chinese consumers while rents of international producers decrease.

Keywords: Steam coal market, China, coal-by-wire, energy market modeling, bulk energy transport

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1. Introduction

Steam coal[1] 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

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

have been shifting to Asia since 2005 (Ritschel, 2009a). An important driver for the future evolution of steam coal market economics will be China as Chinese demand today already makes up 45% of the global market volume[2]. 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 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 (CIRI, 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, 2010).

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 (Sagawa and Koizumi, 2007; Minchener, 2004) 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

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

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 (Fedor, 2008; MIT, 2007).

Nevertheless, the need for a coherent domestic energy transport strategy remains pressing, particularly regarding the continuing consolidation process in the Chinese coal industry (Peng, 2010). 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 (ESMAP, 2008; NDRC, 2007). Consequently, the share of small coal mines in total domestic production dropped significantly from 19.9% (342Mt) in 2003 to 2.1% (55Mt) in 2008 (CIRI, 2008). In addition to the permanent increases in national coal trade volume in recent years, this might have proven to be an additional burden to the prevalent energy transport system, since the restructuring process results in a concentration of production in remote regions in the North and North West of China (Lester and Steinfeld, 2006). Taking these implications of the policy of increased efficiency in the coal industry into account, setting up HVDC transmission lines 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 utilization as well as at the global welfare effects. To analyze these parameters, a spatial equilibrium model which minimizes total costs of global steam coal demand coverage is developed and presented. This global modeling 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 modeling 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. 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, 2010). Coal fields are dispersed widely over the globe, and internationally traded coal is usually transported over long distances to satisfy demand.

Researchers have scrutinized 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 maximization 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, 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. 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 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 and Abbey (1984) analyze strategic behavior 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 modeled 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 analyze 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 organizational 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 utilization 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.

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[3].

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[3] 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

The Pacific market basin saw a large increase not only in domestic production and demand but also in seaward traded volumes (Table 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.

Table 1: Important players in the Pacific basin for 2008 in Mt (IEA, 2009)

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 (Table 2). The U.S. has been a swing supplier in the Atlantic basin, 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 (Ritschel, 2009a; IEA, 2009).

4. The Model

The global steam coal market is modeled 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[4]. 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

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market actors.

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

Table 2: Main players in the Atlantic basin for 2008 in Mt (IEA, 2009)

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

represent haulage tariffs which cover full costs[5]. The global steam coal market is generally considered to be competitively organized and well integrated[6].

4.1. Notation

In this section, the sets, parameters and variables used in the model formulation are described. The time horizon of the model $T = \{2005, 2006, \ldots, t, \ldots, 2040\}$ includes one-year time periods from 2005 until 2015 and five-year time periods from 2015 to 2040[7]. 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 3 and Table 4, respectively.

The mine production cost $C_{m,t}$ is a potentially non-linear function of production volume $S_{m,t}$ and is modeled according to Golombek et al. (1995). In their paper, the authors present a production cost function

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[5] 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.

[6] 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. In the global steam coal market, a large number of both, state-run mining enterprises and privately owned companies compete with each other. According to Ritschel (2010), the largest 10 internationally operating mining companies together controlled only about one quarter of the global hard coal mining production in 2009. Given the availability of additional reserves and potential mining capacity, the potential for enterprises to exercise market power on the global steam coal market currently seems currently quite low. Theoretically, the spatial price equilibrium in such a market is fundamentally marginal cost based (Samuelson, 1952).

[7] Model results will only be analyzed until 2030 to ensure stability of results

Table 3: Model parameters

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

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 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:

$$c_{m,t}(S_{m,t}) = \alpha_{m,t} + \beta_{m,t}S_{m,t} + \gamma_{m,t} \ln\left(\frac{Cap^M_{m,t} + \sum_{t'=2011}^{t} I^M_{m,t'} - S_{m,t}}{Cap^M_{m,t} + \sum_{t'=2011}^{t} I^M_{m,t'}}\right), \quad \alpha_{m,t}, \beta_{m,t} \geq 0,\ \gamma_{m,t} \leq 0, \quad (1)$$

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

4.2. Model formulation

The spatial equilibrium in the global steam coal market is modeled by minimizing the total discounted system costs under a set of restrictions. This formulation is the dual problem within the welfare maximization

Table 4: Model variables

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

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 minimizes 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 minimizing the sum of all cost components:

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

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:

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

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

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

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

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

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

$$S_{m,t} - \sum_{t'=2011}^{t} I^M_{m,t'} - Cap^M_{m,t} \leq 0, \qquad (\lambda_{m,t}) \qquad \forall m, t. \tag{6}$$

The same holds for port capacities:

$$\sum_{i \in I} T_{a_{(p,i)},t} - \sum_{t'=2011}^{t} I^P_{p,t'} - Cap^P_{p,t} \leq 0, \qquad (\phi_{p,t}) \qquad \forall p, t. \tag{7}$$

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

$$\sum_{t'=2011}^{t} I^M_{m,t'} - Cap^{M,max}_{m,t} \leq 0, \qquad (\epsilon_{m,t}) \qquad \forall m, t. \tag{8}$$

The objective function and the restrictions (3) to (8) form the minimization problem WCM. WCM is a convex minimization 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[8].

5. Database

To fully specify the model equations, data on costs and capacities are required. The process of data acquisition is a challenging task in itself, as information on steam coal markets is available only from a multitude of heterogeneous sources. While there are some publications on steam coal markets available from

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

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

5.1. Topology

Table 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 modeled. 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 modeled 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 modeled.

Table 5: Model topology

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

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 by ordinary least squares (an overview of marginal mining costs can be found in the appendix in Table 12). 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 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

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

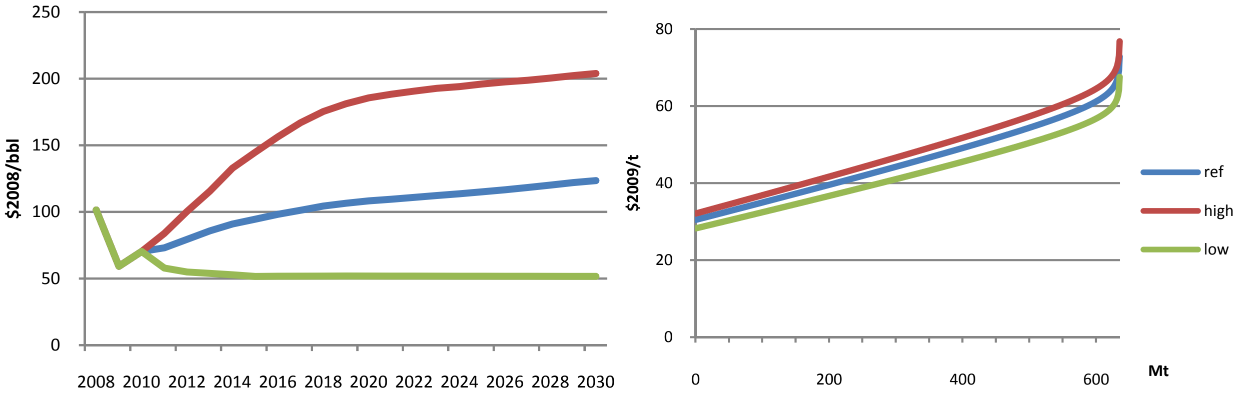

Figure 1: Influence of different oil price projections (left) on the marginal mining costs in Shanxi, China in 2030 (right)

Darmstadter (1999).

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 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.

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

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Table 7: Demand figures for 2005 and 2006 and demand projections until 2030 (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
USA	990	978	914	968
People's Republic of China	1761	1932	3127	4190

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 organizational 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.

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). 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 (Sagawa and Koizumi, 2007; Fedor, 2008). While railway transportation tariffs are high, these tariffs already include mark-ups for investment costs for railway expansion projects[9].

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 (Yinbiao, 2004; Qingyun, 2005). 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 (Minchener, 2007; Fedor, 2008). China lacks a central energy planning institution necessary for the large-scale efficient realization of HVDC grid infrastructure. Approval of large infrastructure investment projects is divided among many different departments. The weakness of central Chinese institutions promotes the assertion currently decisions regarding the energy system in China are often made

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[9] Transporting one tonne of coal from Shanxi to Hong Kong costs about 36 $/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.

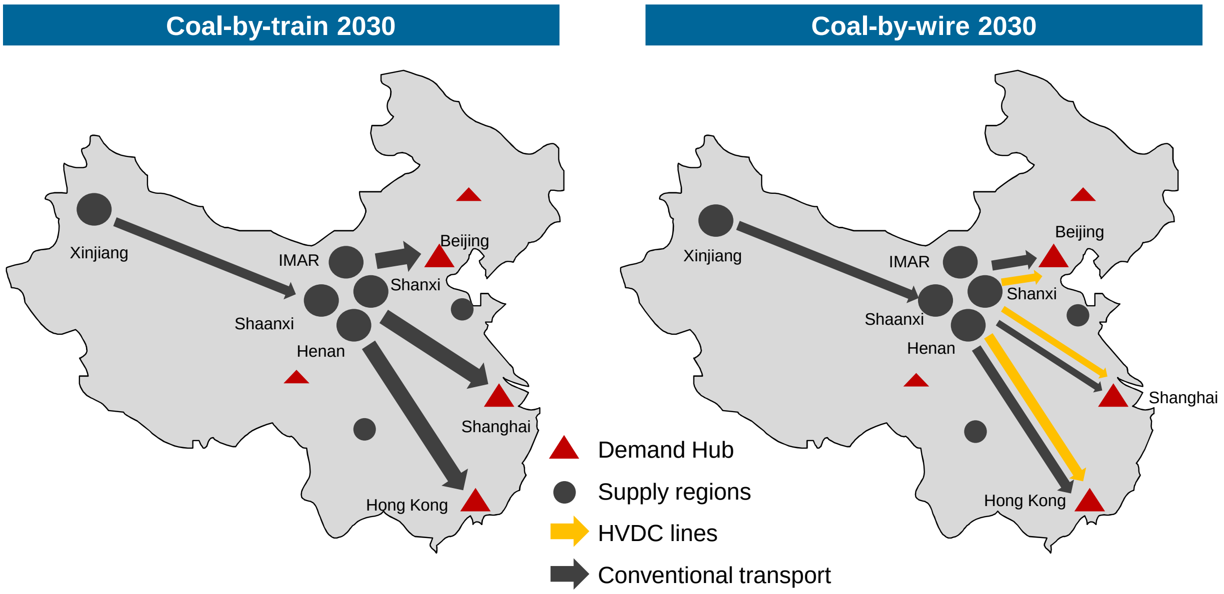

Figure 2: Topology of the scenario setup for China

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 modeled, 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/IMAR, and generated electricity is afterward transported via HVDC transmission to the coastal demand centers.

Table 8: Domestic steam coal transport costs for new-built mines in both scenarios

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

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

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 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.

7. Results

In this section, the main model results for the two analyzed 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 analyzed. A comprehensive overview of model trade flows and marginal costs for all model regions can be found in the appendix.

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 9: Steam coal production, imports and exports in China

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

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

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

[c] *China (reimports)* also 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.

Table 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[10].

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 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

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[10] 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 modeled and are beyond the scope of this analysis.

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 incentivizes investments. Therefore, the scenario results show a strong increase in mining capacity in the west as the mining costs in this region are fairly low, lying in the range of 11 to 22 $\$_{2009}$/t by 2030. With the reduced transport cost burden, these mines 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.

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[11]. As cheaper volumes become available, high-cost suppliers are pushed out of the market and the marginal costs of supply to import regions decline.

Table 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

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

Table 10: Evolution of long-run marginal costs of supply for demand regions in Europe, China and Japan

	2005		2006		2020		2030^b	
in $\$_{2009}$/t (of coal)	Reference[a]	Model	Reference[a]	Model	by-wire	by-train	by-wire	by-train
Beijing	52	51	50	54	63	67	76	97
Shanghai	62	60	58	63	83	88	84	122
Hong Kong	62	60	58	63	83	93	84	126
PRC - West	n/a	53	n/a	56	72	81	108	112
PRC - North	n/a	40	n/a	44	81	85	97	118
Japan	63	60	63	63	83	90	97	121
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 (2009) 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 standardized energy-mass units (25,120 MJ per tonne) while IEA data is in metric tonnes.

investment in 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 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 $\$_{2009}$/t in 2030. However, long railway haulage distances to the export terminals in the Black Sea, the Baltic sea or the Pacific significantly increase costs of supply. Therefore, the difference in marginal costs of supply to Europe of Appalachian mines and the Russian mines is not too large. The difference in European LRMC between both scenarios of approximately 10% to 20% can be basically interpreted as the difference of marginal costs of supply to Europe between the U.S. Appalachian mines and Russian mines in 2030.

The situation for China, however, is different. Here, the marginal supplier changes from high-cost 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 $\$_{2009}$/t to 42 $\$_{2009}$/t in 2030.

7.3. Investment and utilization of mines

Figure 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

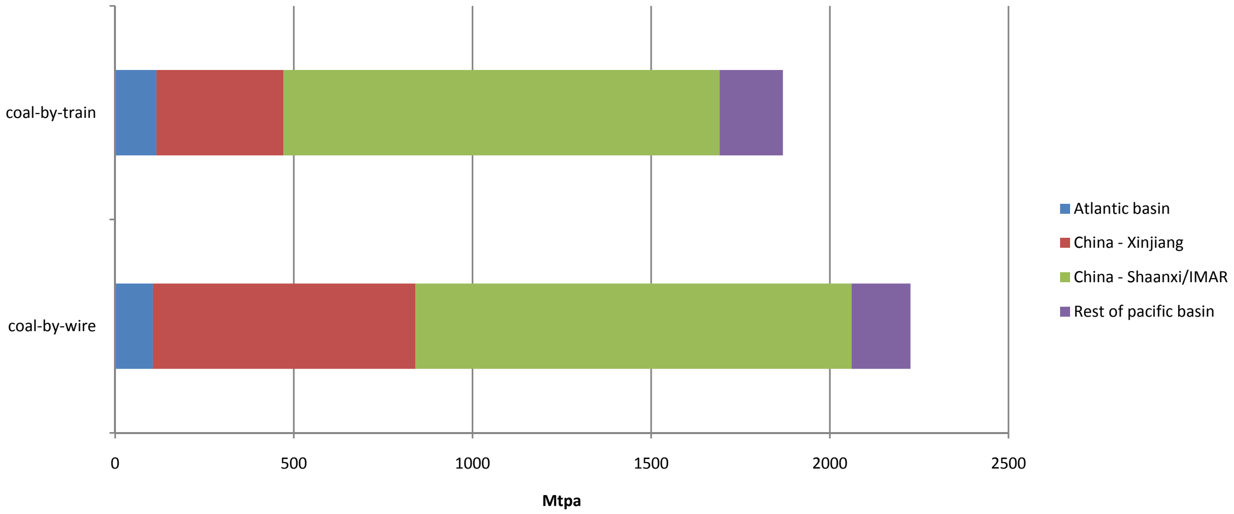

Figure 3: Cumulated mine investments in millions of tonnes per year in the global steam coal market until 2030

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 utilization. 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 11 shows mine utilization levels for Chinese and US mine regions for both scenarios. The main differences in mine utilization 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 utilization 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.

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[12] (Figure 4). In total, gross welfare effects are positive and amount to 248 billion

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

Table 11: Utilization levels of U.S. and Chinese mines

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

$\$_{2009}$ 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 $\$_{2009}$. This is mainly caused by lower global marginal cost levels as well as lower utilization 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 $\$_{2009}$ cumulated until 2030. The biggest portion of this increase is allocated to China, as the difference in marginal costs of supply between both scenarios is the largest there.

To analyze welfare effects of HVDC investments, the net present value of welfare gains or losses and investment costs is computed[13]. The additional HVDC grid which interconnects the mine-mouth coal-fired power plants at new mines in Shaanxi and IMAR with the coastal demand regions of Beijing, Shanghai and Hong Kong amount to 186 billion $\$_{2009}$ until 2030. While these investment figures seem to be high, one must keep in mind the assumption that China is facing an increase of steam coal demand of 2 billion tonnes until 2030. This means an increase of roughly 40% of the current global steam coal demand which only

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[13] 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 realize 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.

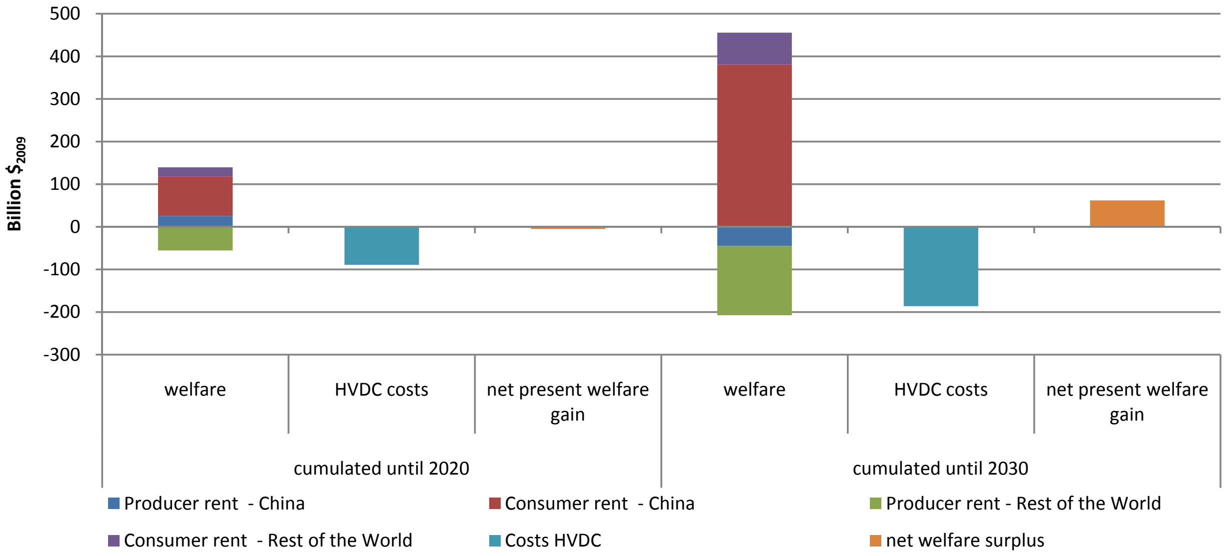

Figure 4: Cumulated net present welfare and cost effects between both scenarios until 2020 and until 2030 (horizontal axis represents the coal-by-train scenario).

takes place in China.

On a global scale, the 'coal-by-wire' configuration leads to cumulated net present welfare gains of -5 billion $\$_{2009}$ by 2020 and 62 billion $\$_{2009}$ by 2030. This may seem quite modest compared to the investment costs and welfare changes involved. However, if the welfare analysis just focuses on China, the picture changes; cumulated net welfare surplus including HVDC investments for China amounts to 28 billion $\$_{2009}$ by 2020 and 149 billion $\$_{2009}$ by 2030. Producers in the rest of the world would be worse off in the coal-by-wire scenario. Production of high-cost mining companies in the U.S. could be crowded out, and cost-competitive suppliers in Australia, South Africa and domestic U.S. suppliers could face severely reduced profits as a results of the price pressure induced by new mines in Xinjiang, Shaanxi and IMAR.

8. Conclusions

This paper analyzes 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 analyzes 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 realization of HVDC transmission lines is hindered by existing organizational 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 (USA) 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 realization, 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.

Appendix

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 (3) to (8) found in section 4 and the following additional equilibrium conditions (9) to (13) .

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 (9) defines the equilibrium condition for inland transport:

$$\mu_{m,t} + d_t \cdot c^T_{a_{(m,p)},t} - \mu_{p,t} \geq 0 \perp T_{a_{(m,p)},t} \geq 0 \qquad \forall m,p,t. \tag{9}$$

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

$$\mu_{p,t} + d_t \cdot c^T_{a_{(p,i)},t} + d_t \cdot c^P_{p,t} + \phi_{p,t} - \mu_{i,t} \geq 0 \perp T_{a_{(p,i)},t} \geq 0 \qquad \forall p,i,t. \tag{10}$$

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 (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:

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

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 (8) is $\epsilon_{m,t}$. This equilibrium condition ensures that investment costs are always amortized 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 (13). The equilibrium condition for ports does not include a Lagrangian multiplier for maximum investments, as maximum port investments are not constrained. Equations (12) and (13) define the equilibrium conditions for mine and port capacity investments:

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

and

$$d_t \cdot c_{p,t}^{I,P} - \sum_{\hat{t}=t}^{T} \phi_{p\hat{t}} \geq 0 \perp I_{p,t}^{P} \geq 0 \qquad \forall p, t. \tag{13}$$

Table 12: Marginal cost data (minimum, maximum and median)

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

Table 13: Projected steam coal trade flows in 2020 and 2030 for both scenarios

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

Table 14: Projected marginal costs of supply in both scenarios

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

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