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COALMOD-World: A Model to Assess International Coal Markets Until 2030*

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Abstract

Coal continues to be an important fuel in many countries' energy mix and, despite the climate change concerns, it is likely to maintain this position for the next decades. In this paper a numerical model is developed to investigate the evolution of the international market for steam coal, the coal type used for electricity generation. The main focus is on future trade flows and investments in production and transport infrastructure until 2030. "COALMOD-World" is an equilibrium model, formulated in the complementarity format. It includes all major steam coal exporting and importing countries and represents the international trade as one globalized market. Some suppliers of coal are at the same time major consumers, such as the USA and China. Therefore, domestic markets are also included in the model to analyze their interaction with the international market. Because of the different qualities of steam coal, we include different heating values depending on the origin of the coal. At the same time we observe the mass-specific constraints on production, transport and export capacity. The time horizon of our analysis is until 2030, in 5-year steps. Production costs change endogenously over time. Moreover, endogenous investments are included based on a net present value optimization approach and and the shadow prices of capacities constraints. Investments can be carried out in production, inland freight capacities (rail in most countries), and export terminals. The paper finishes with an application of the model to a base case scenario and suggestions for alternative scenarios.

Keywords: coal, energy, numerical modeling, investments, international trade.

JEL Codes: L11, L72, C69

1 Introduction

International coal trade has an important role to play in current and future global coal markets. Although the share of internationally traded coal in world coal consumption is relatively small (approx. 16%, IEA, 2009a), it has a major impact on the evolution of domestic markets, and therefore merits extensive analysis. Surprisingly little attention by academic research has been given to specific sectoral analysis of the coal sector. We provide a comprehensive modeling analysis, with a focus on international trade of steam coal.

This paper introduces a tool to analyze the future developments of the international steam coal market, the "COALMOD-World" model. Steam coal is a major fuel for electricity generation today and its use is expected to grow in the coming decades, despite the potential negative external effect on the climate through the CO_2 emissions (IEA, 2009b). The global steam coal trade volume has been increasing in the last years. This trend is expected to continue. An increasing global trade means that more countries will rely on imports. Identifying how the trade flows will develop and where steam coal will come from in the future can help us better assess possible energy security issues.

Since the developments on domestic markets will also affect the future global trade they are incorporated in the analysis. The time horizon is 2006 until 2030. COALMOD-World is a multi-period model that simulates yearly market outcomes, trade flows and prices for the years 2006, 2010, 2015, 2020, 2025 and 2030 as well as investments in the coal sector. We assume profit maximizing players who optimize their (expected and discounted) profit over the total model horizon.

The model setup follows the organization of the value added chain of the steam coal sector. The value chain is complex and there are various types of players involved at each stage. *Producers* can be large national and sometimes state-owned companies. There are a few large multinational coal companies but also many smaller companies, usually operating in one country only. *Transport infrastructure* can be built by the mining company or by another entity. Often, it consists of rail infrastructure but in some countries trucks or river barges are used. *Export ports* can be dedicated to one company or be operated by another company. *Traders* as intermediaries also play a role as they can be vertically integrated or contractually connected to every stage of the industry.

In Haftendorn and Holz (2010), we provide an analysis of the market structure of the global steam coal trade and simplify the value chain for the modeling purpose. There is some evidence that, contrary to the oil market, the international steam coal market tends to be competitive. This result allows us to make some simplifying assumptions for the COALMOD-World model: since in a competitive market prices equal marginal costs, we can simplify the role of the players on the value added chain to obtain two types of model players, the producers and the exporters, shown in Figure 1.

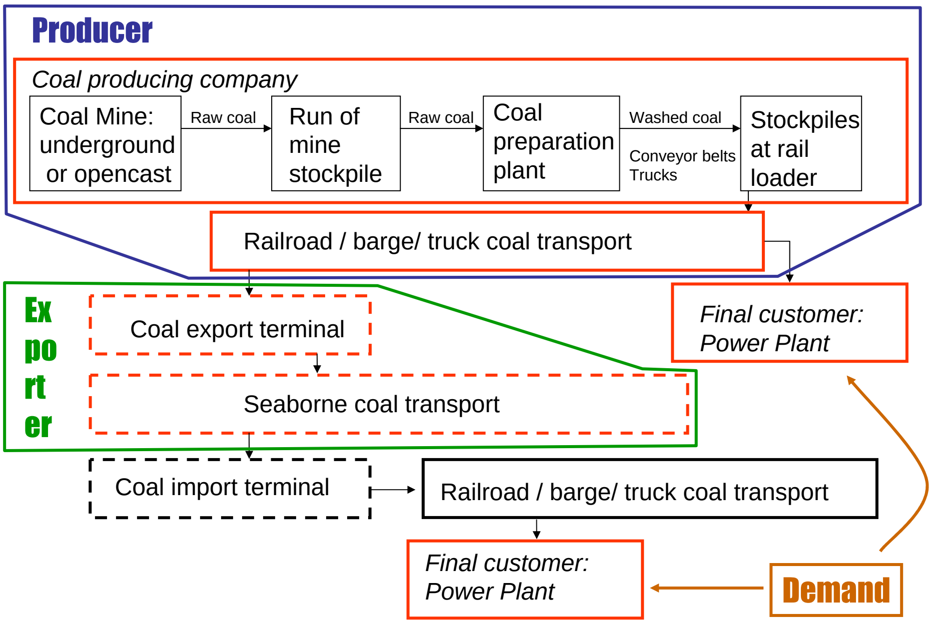

Figure 1: Model players on the steam coal value-added chain

In Figure 1 the steps of the real-world value-added chain that are included in the model are represented by the small rectangles included in the larger producer and exporter boxes. We exclude the coal import terminals and the subsequent land transport link to the final consumer because their capacities are assumed to be sufficient. *De facto*, we situate demand that cannot be reached by land close to the import port. The second type of demand node can be reached by a land link directly from the producer. The producer player includes the coal mining company and also the land transport links. The exporter operates the export terminal and pays for the sea transport. These players are aggregated on a national or regional (sbu-national) level.

Recent research on international coal markets has pointed out that the traditional separation of the Pacific and the Atlantic market has faded (e.g., Ellerman, 1995; Warell, 2006; Li, 2008). In our model, we therefore consider the global market as one integrated market, albeit not neglecting the spatial aspect of the market where transport costs play a role in determining the trade relations.

Simultaneously to the trend of global market integration, we also observe a trend toward commoditization of coal in increasingly liquid market places. This means that coal is traded more and more as a homogeneous good which is reflected by the the creation of price indexes with standardized coal qualities and an increasing volume of paper trade (Zaklan et al., 2009). However, the energy content of steam coal sold on the international market varies depending on the producer. The differences in coal qualities on the international market are not as large as with the coal types that are produced and sold domestically[1] but there are still some significant variations. This suggests to incorporate different coal qualities and to use both types of information, about mass and energy. Previous modeling work also used energy values as we discuss in the following literature review.

The paper provides a detailed description of the model structure and sketches out an application to a "base case" of the world coal developments until 2030. The next section gives an overview of related modeling literature on international energy resource markets such as natural gas and oil. Thereafter, we present the COALMOD-World model. It includes several "innovations" compared to the earlier literature, such as an explicit recognition of coal qualities, production basin-specific supply functions with endogenously changing cost functions over time and a dynamic component allowing for investments in production capacity and infrastructure. An extensive effort of data collection, partially carried out in cooperation with the country teams of the project, is described in Section 4. We then highlight the results of a "base case" in Section 5, specifying the assumptions and providing results until 2030. We observe a significant reorganization of steam coal trade, which is gradually diverted from the Atlantic to the Pacific basin. Section 6 concludes.

2 Equilibrium Modeling of Energy Resource Markets

An extensive review of the – sparse – coal-market specific modeling literature is provided in Haftendorn and Holz (2010). Altogether, there has been little modeling effort applied to international coal markets in general and in particular using modern modeling techniques provided by equilibrium modeling. Kolstad and Abbey (1984) are a notable exception, but their static analysis covered the 1980s. However, both the situation on the international steam coal market as well as modeling techniques have evolved since the 1980s. For several energy and resource markets, multi-period

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[1] Typically, low quality coal such as lignite or low-calorific sub-bituminous coal is sold domestically. The relatively low energy content per ton compared to steam coal makes the long-distance international transport uneconomic.

models with endogenous investments have recently been developed, but to date there has been no such model of the global steam coal market.

We are following the stream of literature of detailed equilibrium (complementarity) models of various resource markets.[2] The development of the COALMOD-World model is rooted in the previous static, one-period model "COALMOD-Trade" (Haftendorn and Holz, 2010), as well as in the multi-period modeling experience of other markets (e.g. Egging et al., 2008, 2010; Huppmann and Holz, 2009). In the following, we present a brief overview of the existing literature of complementarity models with endogenous investment decisions of resource markets.

Complementarity models are numerical models that provide solutions to optimization problems under constraints (e.g. Cottle et al., 1992). The complementarity format can be used to model games, in particular non-cooperative market games such as a Cournot game. The complementarity model gives the Nash equilibrium solution, which is why they are also called equilibrium models. They are formulated by using the optimality conditions (called Karush-Kuhn-Tucker conditions, or KKT) of the optimization problems under constraints.[3] Often, the optimization problems are profit maximization problems of representative player types with some given economic and technical constraints. For a tractable model, some assumptions such as perfect and complete information of all players and over all model periods are generally made.

There has been a large interest in modeling natural gas models in the last years, both on the European and the global scale. Huntington (2009) provides a recent overview of some of these models. Similar to the path that coal market modeling is now taking, there was a predominance of optimization models of natural gas markets for a long time. However, natural gas markets, in particular in Europe, are characterized by strategic behavior with market power exercise. Hence, there has been a need to use a modeling technique such as equilibrium modeling that can represent strategic players. Equilibrium modeling of natural gas markets, first with static models, was initiated by Mathiesen et al. (1987) and especially Boots et al. (2004). Once this model technique was well understood in the static context, the attention turned to the inclusion of investment decisions in a multi-period framework (Lise and Hobbs, 2008; Egging et al., 2010). Endogenous investment decisions in these models are generally limited to the transport infrastructure of pipelines and liquefied natural gas ports, with production capacities given exogenously.

None of the multi-period models of natural gas markets incorporate endogenously

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[2] In this section, we are ignoring the extensive literature on modeling of electricity markets. In this literature, many modeling advances have been made such as the formulation and solution of complex, multi-stage equilibrium problems.

[3] Put simply, these are the first order conditions of the optimization problems.

changing short-term production cost curves. Lise and Hobbs (2008) use long-run marginal costs to incorporate the opportunity costs of production and state that using short-run costs would underestimate the full costs. While this may be true for the gas market we believe that short-term marginal costs curves are better to represent the yearly market outcomes of the coal market. It is also very difficult to obtain long run marginal cost data. In their model, Egging et al. (2010) use the same cost functions for every model year. Hence, in these natural gas market models the cost curves do not vary over time. One exception can be found in Hartley and Medlock (2006) where the long-run production cost curves shift in the future according to an assumed rate of technological innovation in exploration and development costs. However, these changes are exogenous as they are not dependent on the change of other model variables.

There is less literature of equilibrium models of the international oil market. However, many problems are similar to natural gas or coal markets: in the short run, the prevalent market structure is unclear, with the possible economic models ranging from perfect competition to cartel. Moreover, in the long run, capacity expansion both in production and transport infrastructure (ports, pipelines) is an important prerequisite in this market (IEA, 2009b) and needs better modeling. The FRISBEE model (Aune et al., 2005) is a model of the global oil market with a focus on the Organisation of Oil Exporting Countries (OPEC) and its production economics. The Oilmod model (Huppmann and Holz, 2009) includes the price pools in the international market that are reference prices for all international oil sales (e.g., Brent, WTI).[4] These models can include finite resources (reserves) as a constraint to the optimization such that an optimal reserve extraction path (under constraints) is implicitly obtained as solution. We also adopt this approach for the coal market where reserves are globally available for many more decades but may be limiting in the near future for some countries (BP, 2009).

3 The Model

3.1 Model structure

The COALMOD-World model is a multi-period equilibrium model of the global steam coal market with two types of players: producers f and exporters e facing consumers c represented by a demand function. The COALMOD-World's model producers and exporters represent stylized players defined for aggregated production, export and consumption nodes primarily determined using geographical parameters.

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[4] This static version is currently being expanded to a dynamic model with investments.

A production node represents a geographically restricted area (mining basin) and aggregates the mining companies present in that area into one player called producer. In the model, production node and producer are equivalent terms. Production nodes are defined based on the following criteria: geography of reserves, type of coal, and production cost characteristics.

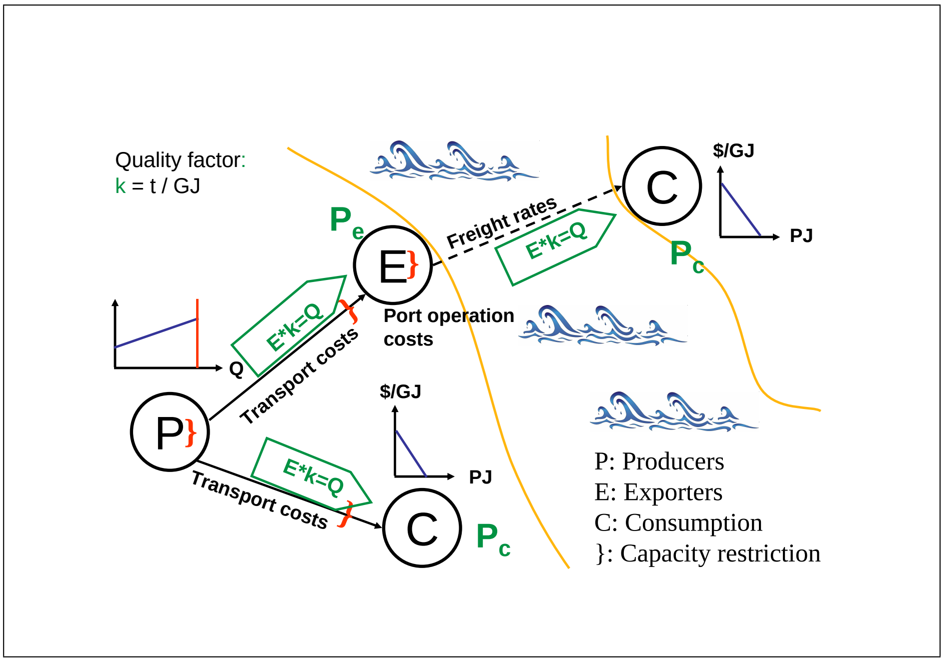

Figure 2: COALMOD-World model structure

An export node represents the coal export terminal of one region and aggregates the real world coal export harbors present in that region into one model player called exporter. Here again, export node and exporter are used as equivalent terms. The export nodes are primarily defined based on geographic factors.

A demand node represents a geographic area where the coal is consumed. It aggregates the consumption by the coal-fired power plants in a region. It can have access to seaborne coal through a port or not. The demand nodes are primarily defined based on geographic factors, but other factors may come into play such as the connection to a port or the presence of mine-mouth power plants.

Figure 2 represents the model structure and the relationships between producers, exporters and demand. The model runs until 2040 and calculates yearly equilibria for the energy quantities sold in the years 2006, 2010, 2015, 2020, 2025, 2030, 2035 and 2040 which we call “model years”. Also, the players can make investments in each model year that will be available in the next model year.[5] Thus, the model does not only calculate an equilibrium within each model year but also over the

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[5] We interpret the results until 2030 because of a risk of distortion of the investment results given the short payback period after 2030.

total model horizon regarding optimal investments. For the years between the model years we intrapolate the produced quantities since they are necessary to model the reserve depletion. We assume that production and other capacities will be made gradually available in the years between the model years to reach their new value in the following model year. Both, producers' and exporters' problems are profit maximization problems over the entire model horizon. The players have perfect foresight, meaning that they choose the optimal quantities to be supplied in each model period and the investments between model periods under the assumption of perfect information both about current and future demand. Thus, the model simulates how demand should be served optimally given that the players behave rationally using all the information that is available to them. In the following section, we present and explain the optimization problems of the model.

It is important to note that the traded quantities x_{afc}, y_{afe} and z_{afc} are the energy quantities contained in the coal, expressed in Petajoules. Whenever the model needs to deal with mass quantities in million tons of coal (for the costs, capacities and investments) these energy quantities are converted in mass using a conversion factor κ defined in tons per Gigajoule that is different for every producer.

3.2 The producers' problem

3.2.1 The producer's profit optimization problem

The producers maximize their profit $\Pi_f^P(x_{afc}; y_{afe};\ Pinv_{af};\ Tinv\_c_{afc};\ Tinv\_e_{afe})$ over the total model horizon A for all model years $a \in A$. The producers extract and treat (produce) the coal and can sell it either to local demand nodes (x_{afc}) or to the exporters (y_{afe}). They bear the production and the inland transport costs. Further, they can invest in additional production capacities ($Pinv_{af}$) and in transport capacities to local demand ($Tinv\_c_{afc}$) or to the exporter ($Tinv\_e_{afe}$). These investments are subject to constraints.

$$\begin{aligned}
&\max_{x_{afc};\, y_{afe};\, Pinv_{af};\, Tinv\_c_{afc};\, Tinv\_e_{afe}} \quad \Pi_f^P(x_{afc}; y_{afe};\ Pinv_{af};\ Tinv\_c_{afc};\ Tinv\_e_{afe}) \\
&= \sum_{a \in A} \left(\frac{1}{1+r_f}\right)^a \cdot \Big[\sum_c p_{ac} \cdot x_{afc} + \sum_e p_{ae} \cdot y_{afe} \\
&- C_{af}^P \left(\sum_c x_{afc} \cdot \kappa_{af} + \sum_e y_{afe} \cdot \kappa_{af}\right) \\
&- \sum_c trans\_c_{afc} \cdot x_{afc} \cdot \kappa_{af} - \sum_e trans\_e_{afe} \cdot y_{afe} \cdot \kappa_{af} \\
&- Pinv_{af} \cdot CPinv_{af} \\
&- Tinv\_c_{afc} \cdot CTinv\_c_{afc} - Tinv\_e_{afe} \cdot CTinv\_e_{afe}\Big]
\end{aligned} \tag{1}$$

s.t.

$$Pcap_f + \sum_{a'<a} Pinv_{af} - \left(\sum_c x_{afc} \cdot \kappa_{af} + \sum_e y_{afe} \cdot \kappa_{af}\right) \geq 0 \qquad \left(\alpha_{af}^P\right) \tag{2}$$

$$Pmaxinv_{af} - Pinv_{af} \geq 0 \qquad \left(\alpha_{af}^{Pinv}\right) \tag{3}$$

$$\begin{aligned}
&Res_f - \sum_{a \in A} \Big[\Big(\sum_c x_{afc} \cdot \kappa_{af} + \sum_e y_{afe} \cdot \kappa_{af} \\
&+ \sum_c x_{a-1fc} \cdot \kappa_{a-1f} + \sum_e y_{a-1fe} \cdot \kappa_{a-1f}\Big) * \frac{5}{2}\Big] \qquad \geq 0 \qquad \left(\alpha_f^{Res}\right)
\end{aligned} \tag{4}$$

$$Tcap\_c_{fc} + \sum_{a'<a} Tinv\_c_{afc} - x_{afc} \cdot \kappa_{af} \geq 0 \qquad \left(\alpha_{afc}^{Tcap\_c}\right) \tag{5}$$

$$Tcap\_e_{fe} + \sum_{a'<a} Tinv\_e_{efc} - y_{afe} \cdot \kappa_{af} \geq 0 \qquad \left(\alpha_{afe}^{Tcape}\right) \tag{6}$$

$$Tmaxinv\_c_{afc} - Tinv\_c_{afc} \geq 0 \qquad \left(\alpha_{afc}^{Tinv\_c}\right) \tag{7}$$

$$Tmaxinv\_e_{afe} - Tinv\_e_{afe} \geq 0 \qquad \left(\alpha_{afe}^{Tinv\_e}\right) \tag{8}$$

$$x_{afc} \geq 0;\ y_{afe} \geq 0;\ Pinv_{af} \geq 0;\ Tinv\_c_{afc} \geq 0;\ Tinv\_e_{afe} \geq 0 \tag{9}$$

In the second line of the producers' objective function (1) we can see the summation of the yearly net revenues in the squared brackets over all model years with the associated discount rate r_f. The following two terms after the brackets are the revenues from sales to local demand nodes and to exporters. This term would be different in case the producer exerts market power: it would include the demand function of the local consumption nodes and not only the equilibrium price. The third line of (1) shows the production cost function in an undefined form. The fourth line of (1) represents the transport costs to local demand and exporters. Line five of (1) calculates the total investment costs in production capacity and line six does the same for the investments in transport capacities to local demand and exporters.

The constraints are valid for each model year except the constraint on the reserves (4) which has to hold over the total model horizon. Equation (2) represents the production capacity constraint for one year which depends on the capacity in the starting year and investments in subsequent periods prior to the model year. Equation (3) is a restriction on the maximum investments in production capacity that can be build up during the next five years (i.e. until the next model year). (4) is the reserve constraint of the producer over the total model running time and includes reserve utilization from the production of the years between the model years. On the domestic transport market we have (5) and (6) which are the transport capacity constraints for each model year for transport routes to local demand nodes and exporters, respectively. (7) and (8) are the respective maximum investments in additional transport capacity similarly to (3). The symbols in parentheses are the dual variables associated with the constraints and (9) are the non-negativity constraints of the decision variables.

3.2.2 The production cost function

In this section, we specify the production cost functions of each period that were left undefined in Section 3.2.1. Since the cost functions appear in each period, we also call them short-run cost functions. Generally, we assume a quadratic cost function of the type:

$$C_f = (mc\_int_f + \frac{1}{2} \cdot mc\_slp_f \cdot q_f) \cdot q_f \tag{10}$$

This leads to the following linear marginal cost function:

$$mc_f = mc\_int_f + mc\_slp_f \cdot q_f \tag{11}$$

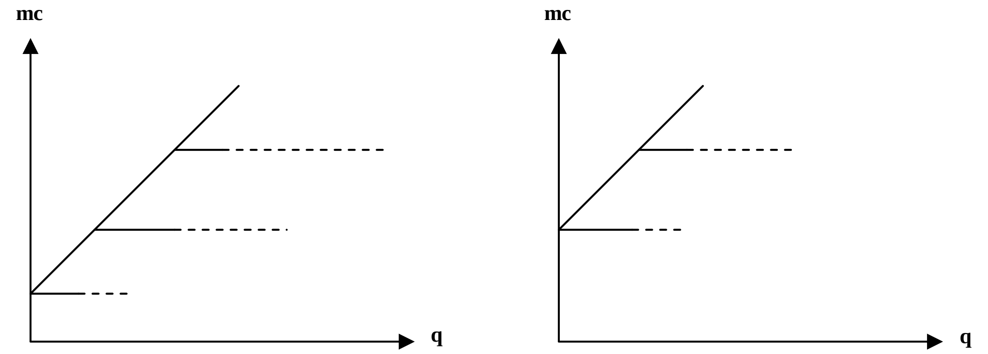
Since we have an energy based model but mass dependent production costs, we use the conversion factor κ_f explained in detail in Section 3.4 to obtain the following marginal cost function depending on the quantity q_f expressed in energy units:

$$\kappa_f \cdot mc_f = \kappa_f \cdot mc\_int_f + \kappa_f \cdot mc\_slp_f \cdot q_f \tag{12}$$

Some resource markets models use the same short-run costs for every model period (e.g. Egging et al., 2010). This is not a realistic solution for a model of the coal market since there are many potential factors that influence future costs and change the short run costs. Other models only use the long run marginal costs (e.g. Lise et al., 2008). This is also problematic for a model of the coal market since the short-term marginal costs determine the prices in each period and, as we have seen in our previous static modeling work (Haftendorn and Holz, 2010), enable us to represent the trade flows accurately. In the following, we discuss the influential factors and their impact on the short-run cost functions.

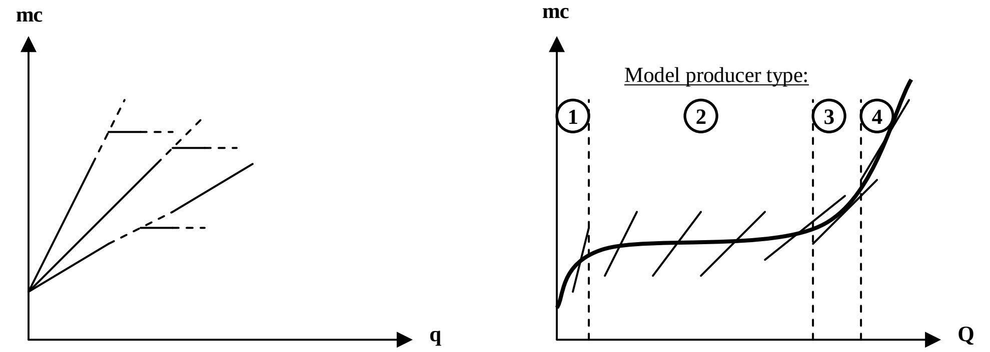
Geological factors are the main driver and reason for variability between production costs as described in BGR (2009). First we can distinguish between opencast and underground mining. Furthermore, the geological structure of the deposit such as the thickness and depths of the seams as well as their inclination and the nature of the geological formation that hosts the seams influence the mining costs. On the techno-economic side Rogner (1997) identifies future rates of technology change as well as productivity gains as critical drivers for potential future production costs. For our own assessment we primarily use the geological factors and to a lesser extend assumptions about the potential for productivity gains. Other factors that affect production costs and trade such as exchange rates, prices for equipment or fuel prices are not considered since they are either difficult to predict or they affect all producers more or less equally.

At the highest level of aggregation Rogner (1997) found that the long-run production cost curves for all fossil fuels (oil, natural gas and coal) over the total potential reserves have an S-shaped form similar the one shown in Figure 3d. We assume that a mining basin, because it also represents a high level of aggregation, has a similar cost development as the cumulated production increases. The exact form of the curve may vary but it is important to distinguish four types of situations that a mining basin will be in over its lifetime as shown in Figure 3d. First, a mining basin has some very accessible resources (often the cause of an accidental discovery). But since these resources are limited production costs increase rapidly. Second, the production costs reach a relative plateau, as the bulk of the reserves are similar in nature. Third, when the bulk of the reserves is mined out, the costs start to increase



a. Aggregation from the individual mines' marginal costs to the model producers' (mining basin) marginal cost curve.

b. Effect of cumulated production on the intercept of the model producers' short-run marginal cost curve.



c. Effect of new investments in production capacity on the slope of the producers' short-run marginal cost curve.

d. Long-run marginal cost curve and short-run marginal cost curves over the lifetime of a mining basin.

Figure 3: Endogenous cost mechanism in relation with short and long-run marginal costs

more or less proportionally with the cumulated production. Fourth and finally, only deposits that are hard to reach remain to be mined and the extraction costs rise rapidly. Each coal mining basin can be put in relation with one of these four types. Consequently, we assign each producer to one such type. This determines how the short-run costs will develop in the next 20 years. Before we categorize the producers we explain the endogenous cost mechanism starting at the individual mine level.

Figure 3a shows the logic of aggregation of individual mines in a mining basin to form the model producers' marginal cost curves. We assume that a specific mine with a certain geological setting operates at constant marginal costs. The horizontal line together with the dashed line represent the reserves of a mine. The horizontal line represents the production capacity at a given point in time. Thus, in order to obtain the aggregated cost curves in one period we add the production capacities on the q-axis and connect them with their respective marginal costs on the mc-axis.

After this static consideration, let us consider how this cost function might evolve over time. We first consider the effect of cumulated production as illustrated in

Figure 3b. We assume that, even if all the mines along the cost curve may produce coal in one period, the cheapest mines are depleted first. Thus, we follow the rules stated by Hotelling (1931) that for exhaustible resources the cheapest deposits are extracted first. The principal reason is that the cheap mines generally are the oldest ones in operation. The effect of cumulated production from one model period to another is then that the cheapest producer in Figure 3a disappears from the cost curve. This causes the intercept of the cost function to increase as shown in Figure 3b. This is the core of the first endogenous cost mechanism that enters the model with the following equation:

$$\begin{aligned} mc\_int_{af} &= mc\_int_{(a-1)f} \\ &+ mc\_slp_{(a-1)f} \cdot \left(\sum_c x_{(a-1)fc} \cdot \kappa_{(a-1)f} + \sum_e y_{(a-1)fe} \cdot \kappa_{(a-1)f} \right) \cdot mc\_int\_var_f, \\ & mc\_int_{af} \text{ (free)} \end{aligned} \tag{13}$$

Equation 13 states that the **intercept** in year a is equal to the previous period's intercept plus the previous period's slope multiplied by the production in that year and the factor $mc\_int\_var_f \in [0,1]$. The factor $mc\_int\_var_f$ determines how fast the cheapest mines are mined out. It gives the position on the cost curve of the previous period to determine the new intercept. Graphically, this is the passage from Figure 3a to 3b. If the factor is one it means that the cumulated production leads to a complete depletion of the oldest, cheapest mines. This may be true for mature and old mining basins. On the contrary, a factor close to zero means that the mines situated on the low cost segment of the basin's cost curve still have significant reserves and will only be depleted in the mid to long-term.

The second endogenous cost mechanism included in the model simulates the effect of new investments in production capacity or the addition of new mines on the **slope** of the marginal cost curve. Graphically, this is represented by the step that leads from Figure 3a to Figure 3c. Mathematically, this mechanism is described by the following equation:

$$mc\_slp_{af} = mc\_slp\_start_f + mc\_slp\_var_f \cdot \sum_{a'<a} Pinv_{a'f}, \quad mc\_slp_{af} \text{ (free)} \tag{14}$$

The factor $mc\_slp\_var_f \in \mathbb{R}$ in equation 14 represents the effect of the cumulated investments in production capacity on the slope of the marginal cost curve. A value of zero is used for the case that there is no influence of the investments on the slope (model producer type 3). A negative value of $mc\_slp\_var_f$ causes the slope to decrease (model producer type 2) and a positive value increases the slope with new investments (model producer type 1 and 4).

In order to implement this mechanism we add the two equality constraints (13 and 14) and their respective complementarity variables to the producer's problem. The two equations are affine; thus, the KKT conditions are sufficient conditions for optimality. The overall problem remains convex.[6]

3.3 The exporters' problem

The exporters maximize their profit $\Pi_e^E(z_{aec};\, Einv_{ae})$. Each producer is linked to a maximum of one exporter.[7] The profit for each year shown in (15) inside the squared brackets is defined by the revenue from sales net of the costs of purchasing the coal at a FOB price p_{ae} from the producer in the second line, the costs of operating the export terminal in the third line, the costs of transport (shipping) to the final market c in the fourth line and finally in the last line the costs of investing in additional export capacity. The yearly profits are summed over the total model years and discounted by a rate r_e. The index c represents a demand node. An exporter can only sell to a demand node with a port. The exporter's decision is to choose the optimal quantity z_{aec} to sell to each importing country c in each year a and also to invest in export capacity $Einv_{ae}$. In case the exporter exerts market power, the revenue term would include the demand function of the importing node instead of the price.

$$
\begin{aligned}
\max_{z_{aec};\, Einv_{ae}} \quad \Pi_e^E(z_{aec};\, Einv_{ae}) = \sum_{a\in A} \left(\frac{1}{1+r_e}\right)^a \cdot \\
\Big[\sum_c p_{ac}\cdot z_{aec} - \sum_c p_{ae}\cdot z_{aec} \\
- \sum_c z_{aec}\cdot Cport_{ae}\cdot \kappa_{ae} \\
- \sum_c z_{aec}\cdot searate_{aec}\cdot \kappa_{ae} \\
- Einv_{ae}\cdot CEinv_{ae}\Big]
\end{aligned}
\qquad (15)
$$

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[6] The only detail that has to be watched is in the case of a negative parameter $mc\_slp\_var_f$. If this parameter is not chosen correctly in the calibration process and is set very low, there is a risk that equation 14 calculates a negative value for the slope mc_slp_{af}. This would make the model non-convex and infeasible to solve. A careful calibration based on geological and techno-economical information wards off such a risk since in reality we do not expect changes in the slope to be too drastic.

[7] Another model structure with the possibility for an exporter to serve several producers was also tested but its implementation was not necessary to represent the global coal market accurately.

s.t.

$$Ecap_e + \sum_{a'<a} Einv_{ae} - \sum_{c} z_{aec} \cdot \kappa_{ae} \geq 0 \quad \left(\mu_{ae}^{E}\right) \tag{16}$$

$$Emaxinv_{ae} - Einv_{ae} \geq 0 \quad \left(\mu_{ae}^{Einv}\right) \tag{17}$$

$$Emaxcap_e - Ecap_e - \sum_{a} Einv_{ae} \geq 0 \quad \left(\mu_{e}^{Emax}\right) \tag{18}$$

$$z_{ec} \geq 0;\ Einv_{ae} \geq 0 \tag{19}$$

Constraint (16) represents the maximum export capacity in each model year which depends on the capacity in the starting year and investments in subsequent periods prior to model year a. Equation (17) expresses the maximum investments in export capacity for one model year. (18) represents the maximum possible investments over the total model horizon until 2040. This constraint allows the model to determine endogenously in which model year the port expansions should take place. The symbols in parentheses are the dual variables associated with the constraint.

3.4 Quality equation

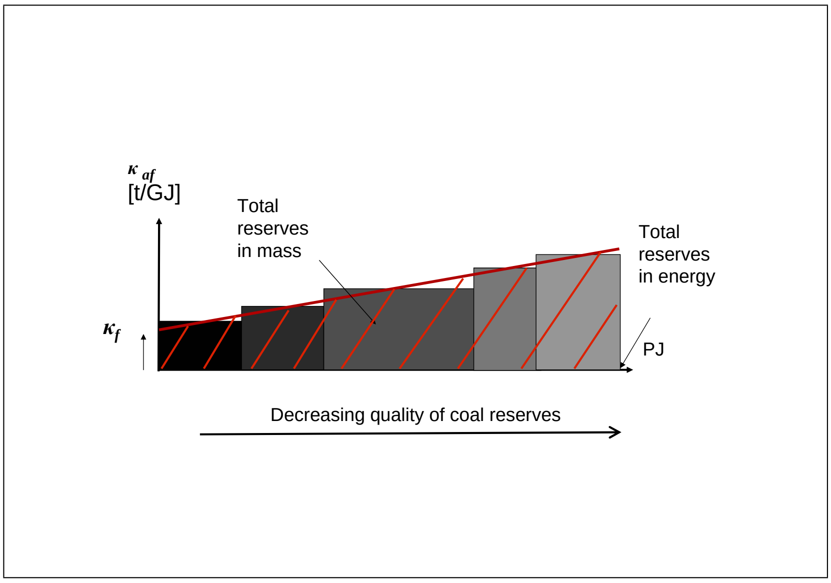

Figure 4: Producer's quality definition relative to its reserves

Since each model producer represents an entire mining basin with various mines and significant amounts of reserves, the quality of the produced coal may not be constant over time. Figure 4 visualizes this fact and shows how it affects the model. The x-axis represents the energy value of the reserves and the y-axis the quality factor κ associated with the reserves. The areas in this graph represent million tons. For one model producer, we have different reserve blocks represented by the black to gray blocks. We assume that the higher quality coals are mined first, thus the reserve blocks are ordered by decreasing coal quality. Using this information we obtain the increasing line over the hatched area by using a linear regression. Equation (20) formulates this relationship between reserves and coal quality mathematically.

$$\kappa_{af} = \kappa_f + \delta_f \cdot \sum_{a' \leq a} \left(\sum_c x_{afc} + \sum_e y_{afe} \right) \tag{20}$$

Since each model exporter has a dedicated model producer, the quality factor κ_{ae} of the exporter is equal to the quality factor of the producer that supplies him for any given year.

3.5 Final demand

Final demand is located at a consuming node c. The following market clearing condition determines the price given the demand function $p_{ac}\left(x_{afc}, z_{aec}\right)$ at the demand node.

$$p_{ac} - p_{ac}\left(\sum_f x_{afc}, \sum_e z_{aec} \right) = 0 \quad , p_{ac} \text{ (free)} \tag{21}$$

The producers can be in indirect contact with the final demand through their exporter or in direct contact with their domestic demand. The prices are expressed in USD per GJ, because we concentrate on the demand for energy embodied in the coal.

We assume a linear inverse demand function of the type $p_{ac} = a_{ac} + b_{ac} \cdot q_{ac}$ for each consumer c in each model year a. We construct a different linear inverse demand function for each demand node c using their reference prices (p_{ac}^{ref}) and reference demand value (q_{ac}) for the model starting year 2006 and use projections for future years. We make assumptions on the demand elasticities (ε_{ac}). In particular, we define $b_{ac} = \frac{p_{ac}^{ref}}{q_{ac}^{ref}} \cdot \frac{1}{\varepsilon_{ac}}$ and $a_{ac} = p_{ac}^{ref} - b_{ac} \cdot q_{ac}^{ref}$, following the demand elasticity definition $\varepsilon_c = \frac{q_{ac} - q_{ac}^{ref}}{p_{ac} - p_{ac}^{ref}} \cdot \frac{p_{ac}}{q_c}$. This gives the following inverse demand function depending on the consumed quantity $q_{ac} = \sum\limits_{f} x_{afc} + \sum\limits_{e} z_{aec}$:

$$p_{ac} = p_{ac}^{ref} + \frac{1}{\varepsilon_{ac}} p_{ac}^{ref} \left(\frac{q_{ac}}{q_{ac}^{ref}} - 1 \right) \tag{22}$$

3.6 Market clearing

In addition, one must consider market clearing conditions ensuring that the coal sold by the producer to the exporter in a node equals the coal sold by the exporter to all the importing demand nodes. This condition also determines the price p_{ae} at the exporting node.

$$0 = y_{afe} - \sum_{c} z_{aec} \quad , p_{ae} \text{ (free)} \tag{23}$$

3.7 China's export restriction

Modeling China's export restriction requires the additional equation (24). The Chinese coal exports are restricted by politically determined export licenses. Thus we put a constraint on all consumption nodes with a non-Chinese import port (i.e., countries $NoChina(c)$) using equation (24). $China\_lic_{a\,E_{CHN}}$ represents the level of Chinese export licenses for a given year in million tons.

$$China\_lic_{a\,E_{CHN}} - \sum_{NoChina(c)} z_{aec} \cdot \kappa_{ae} \geq 0 \quad (\pi_{a\,E_{CHN}}) \tag{24}$$

4 Model Specification and Data

In Section 3.1 we have introduced the concepts of nodes and model players. The model simulates the market on an aggregated basis, that is we do not include individual mines or coal-fired power plants. However, the spatial characteristics of the market and the transport costs associated with that spatial aspect make it necessary to define aggregated nodes in the different producing and consuming countries. Section 4.1 describes our choice of model countries and nodes before providing a detailed overview of our data in the subsequent sections.

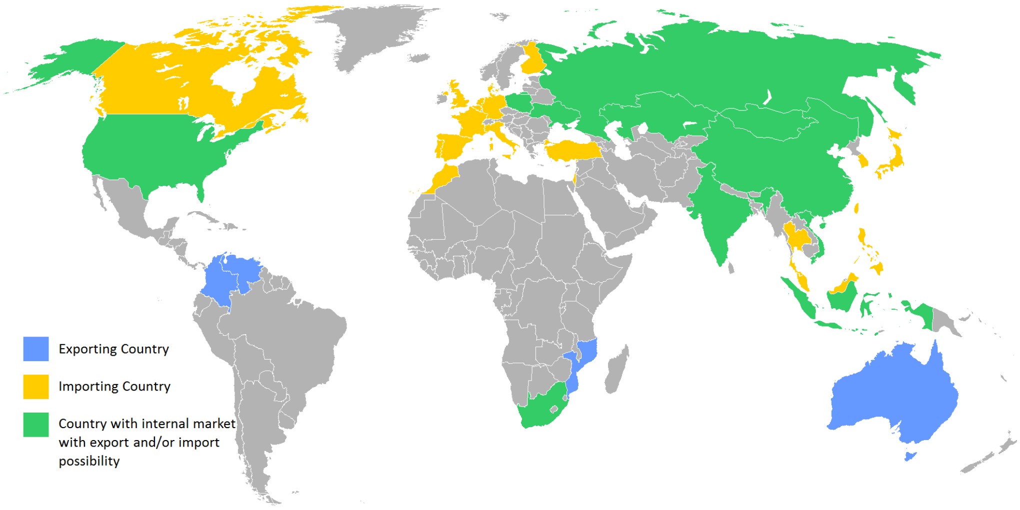

Figure 5: Countries included in the COALMOD-World data base

4.1 Countries and nodes definition

We include all countries that were either consuming at least 5 mtpa[8] or producing and exporting at least 5 mtpa in 2006. Some more countries that are expected to become relevant players on the global market in the next decades are included, too (e.g., Mongolia, Mozambique). The world map in Figure 5 shows the represented countries including their role on the world coal market (importer, exporter, or both).

In our data set, we distinguish production and consumption nodes. Hence, a country that only produces for export is represented in the data set with a production node from which it also exports (e.g., Colombia). A country that only imports and consumes coal is included with a consumption node (e.g., Italy, Turkey). For a country in which production takes place and that also consumes coal, we include at least one production node and one consumption node. For larger countries, there can be more than just one production/demand node; this is the case for the U.S., China, India and Australia. The complete list of the countries and nodes in the model can be found in Table 4 in Appendix B.

Producing nodes are generally defined by mining basins which are restricted by geological realities. The location of power plants is more dispersed as it relates to human settlements. This makes it more difficult to locate our consuming nodes. For the consumers that can only be reached through an importing port we define the demand as being located close to the port. For consumers that can be reached by land we aggregate regional data on capacities to form the demand node and define an average for the transport costs.

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[8] Mtpa: million tons per annum.

4.2 Production, costs and reserves

The data collection required a major effort since there is no central source available. We collected data from publicly available sources, that are detailed in the following.[9] Most of the cost data is based on Baruya (2007): "*Supply costs for internationally traded coal*" (IEA Clean Coal Center). For each export country, Baruya (2007) provides estimates for the low and high average costs. This information is used to construct the producers' cost functions of the base year. We assume that the average costs also represent unit costs for the cheapest and the most expensive mine. Thus, in the short run we have the same variable costs and marginal costs for one mine. We construct a marginal cost function using the low estimate to determine the curve intercept. We place the second point at the intersection of the high cost estimate and the maximum production capacity in order to obtain a linear marginal cost curve as described by Equation (11) in Section 3.2.2.

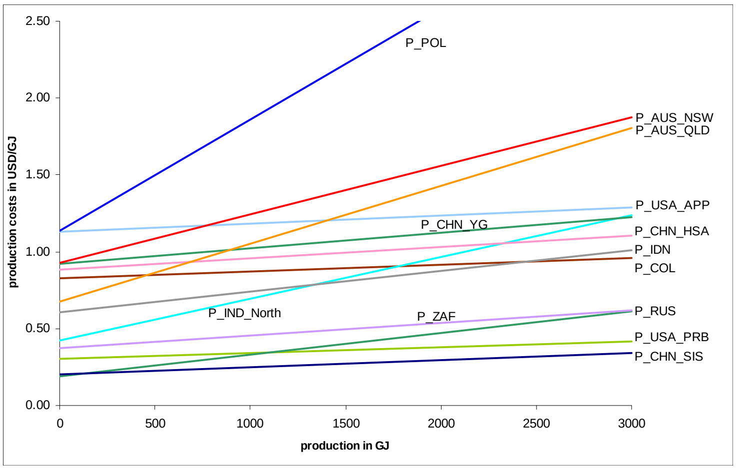

Figure 6: Marginal cost curves 2006 for selected production nodes (Source: own work based on Baruya, 2007; Rademacher, 2008; Energy Information Administration, 2008; National Bureau of Statistics of China, 2007; New South Wales Department of Primary Industries, 2009; Queensland Department of Mines and Energy, 2009; Datanet India, 2009; Ritschel and Schiffer, 2005; Geological Survey of India, 2008)

In Figure 6 we depict the marginal cost curves for the base year 2006, the full set of marginal cost curve parameters is given in Appendix C. One can see that the different production regions in a large country (e.g. in China) can well have different production costs. As would be expected, Poland is the most expensive producer on

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[9] Overall there is some scarcity of data in the public domain and improvements could be provided by using more detailed data. The model would especially benefit from better cost data since it is a competitive, cost-driven model. With accurate cost data and projections, the model could even be used to deliver forecasts of future prices to a certain extent. Despite the issues mentioned above the COALMOD-World database is able to provide realistic runs and give insights into the future developments of the global steam coal market as is shown in Section 5.

the world market, while some Chinese regions (Shanxi, Shaanxi, Inner Mongolia), the Powder River Basin (USA) and South Africa are on the lower end.

For the producers from Eurasia, Colombia, Venezuela, South Africa and Indonesia, the cost data and the parameters of the marginal cost function are based on Baruya (2007); the capacity data is based on Rademacher (2008), except for Eurasia where the capacity data is based on actual production assuming a capacity utilization of 90%. Countries with more than one production node require more detailed data on production capacities that was determined using the following sources: for the USA, Energy Information Administration (2008, Tables 1 and 12); for China, data from the National Bureau of Statistics of China (2007); and for Australia, data from the New South Wales Department of Primary Industries (2009) and the Queensland Department of Mines and Energy (2009) with a capacity utilization assumption of 80% (Rademacher, 2008, p. 78).

For Vietnam, the production capacity is taken from Rademacher (2008). For India the actual production data from Datanet India (2009) is used, assuming 90% capacity utilization. This assumption is also made for Poland using IEA (2008a). The Indian cost data is based on average cost data for each subsidiary company of *Coal India Ltd.*. Since there was no cost data available for Vietnam, these were determined using relevant price data. For Poland, the costs are based on Ritschel and Schiffer (2007).

In order to determine the cost functions in the long run, some assumptions on the mining basin types and the intercept increase pace had to made. Table 7 shows these assumptions and the values of $mc\_slp\_int_f$ and $mc\_slp\_var_f$. The assignment of the model producers to a producer type is based on informations about geological factors of each basin, the age of mines, as well as the prospects of future productivity improvements. The main sources for this assessment are Minchener (2009), EPRI (2007) and Ritschel and Schiffer (2007). For the USA the report by Luppens et al. (2009) that is part of the National Coal Resource Assessment Overview was used.

In Figure 7 we depict the distribution of global steam coal reserves by major global producing regions. In order to use consistent reserves data, we base ourselves primarily on one source: Energy Information Administration (2008, Table 8.2). It follows the standard definition of reserves by the World Energy Council:

> “proved recoverable reserves are the tonnage within the proved amount in place that can be recovered (extracted from the earth in raw form) under present and expected local economic conditions with existing available technology” (Energy Information Administration, 2008).

This data is aggregated on a national level, thus to get the distribution on a sub-

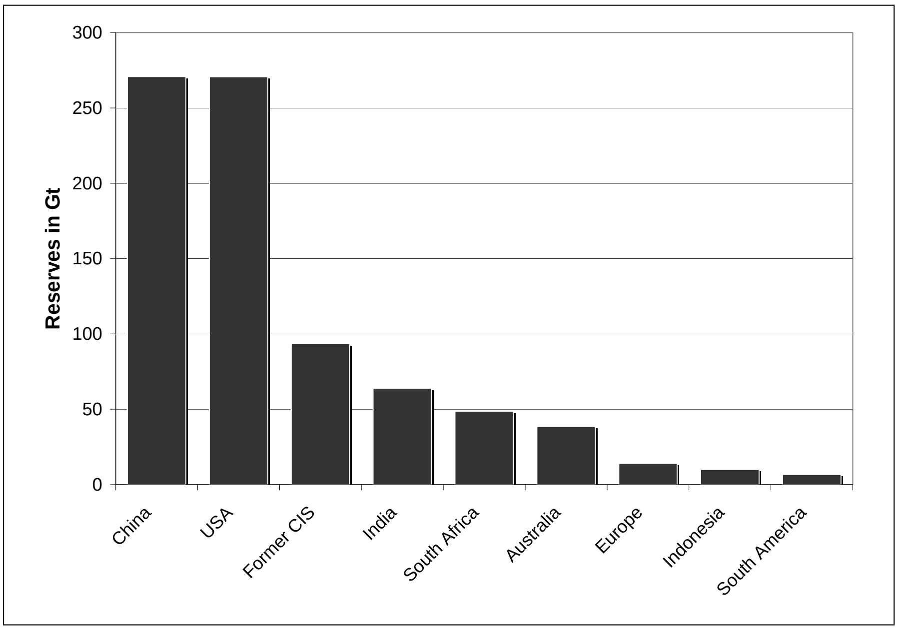

Figure 7: Reserves of major countries in COALMOD-World (Source: own work based on Energy Information Administration, 2008; Geological Survey of India, 2008; National Bureau of Statistics of China, 2007)

national level other sources had to be used. For the USA, Energy Information Administration (2008, Table 15) was used. The reserve distribution to the Indian production nodes is based on the Geological Survey of India (2008) and for the Chinese producers on the National Bureau of Statistics of China (2007).

The coal quality data κ_f is shown in Table 1. It is based on Platts (2009) for the USA, Colombia, Venezuela, Poland, Russia, South Africa, Indonesia and Australia. For China, it is based on IEA (2007) and for India on Datanet India (2009)[10]. For Vietnam the quality data is taken from Ritschel and Schiffer (2007).

The Energy Watch Group (2007) provides evidence that coal quality is generally decreasing over time as the reserves are mined. According to this study the decline in coal quality is not only due to a shift toward lower rank coals, like sub-bituminous coals, but also to a quality decline within each class. This is the reason why we implement this effect in the model through the factor δ_f introduced in Section 3.4. However, no consistent data is available for all production nodes and we are using $\delta_f = 0$, implying no quality variation over time. The model still captures some of this effect through the different coal qualities of the producers. For example, if the recent developments in the USA continue with more (lower grade) coal from the Powder River basin being produced, the overall quality of U.S. coal will decrease.

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[10] Spreadsheet: *Grade/Company-wise Production of Non-Coking Coal, 1999-2000*

Table 1: Energy content and quality κ_f of coal by production nodes (Source: own work based on Platts, 2009; Datanet India, 2009; Ritschel and Schiffer, 2007)

Node	Calorific value in kcal/kg	Energy content in GJ/t	κ_f in t/GJ
P_USA_PRB	8600	20.00	0.04999
P_USA_Rocky	11400	26.52	0.03771
P_USA_ILL	11200	26.05	0.03839
P_USA_APP	12500	29.08	0.03439
P_COL	6375	26.69	0.03747
P_VEN	7000	29.31	0.03412
P_POL	6300	26.38	0.03791
P_UKR	6200	25.96	0.03852
P_KAZ	6000	25.12	0.03981
P_RUS	6400	26.80	0.03732
P_ZAF	6400	26.80	0.03732
P_IND_North	4260	17.83	0.05607
P_IND_Orissa	3041	12.73	0.07854
P_IND_West	4187	17.53	0.05704
P_IND_South	4187	17.53	0.05704
P_VNM	7000	29.31	0.03412
P_IDN	5450	22.82	0.04382
P_CHN_SIS	6100	25.54	0.03916
P_CHN_Northeast	5600	23.45	0.04265
P_CHN_HSA	5400	22.61	0.04423
P_CHN_YG	5200	21.77	0.04593
P_AUS_QLD	6500	27.21	0.03675
P_AUS_NSW	6300	26.38	0.03791
P_MNG	6100	25.54	0.03916
P_MOZ	6400	26.80	0.03732

4.3 Land transport

The land transport costs ($trans\_c_{afc}$, $trans\_e_{afe}$) and capacities ($Tcap\_c_{fc}$, $Tcap\_e_{fe}$) are associated with the transport from a producer to local demand or to an exporter. This represents mainly transport by train but can also include road transport on trucks and in certain cases river transport by barges. The transport costs are assumed to be constant over time.

The transport costs for Colombia, Venezuela, South Africa, Indonesia, China and Australia are based on Baruya (2007). For these countries, transport capacity data is based on relevant production, consumption and export data. For the USA, this data is based on Energy Information Administration (2004) for the transport costs. The transport capacities inside the USA are determined using actual flow data given in Energy Information Administration (2007).[11] The transport cost data

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[11] Spreadsheet *Domestic Distribution of U.S. Coal by Origin State, Consumer, Destination and*

for the Eurasia region is from Crocker and Kovalchuk (2008) and the capacities are determined using relevant production, consumption and export data. This method is also used to estimate the transport capacities in Vietnam and India. The Vietnamese costs were based on relevant price data. The Indian transport cost data is based on Datanet India (2009).[12]

4.4 Export ports

The data for the export ports includes the export capacity in the starting year and the port handling costs. For Colombia, the Eurasia region, South Africa and Australia, the capacity data is taken from Ritschel and Schiffer (2007) and the cost data from Baruya (2007). For Venezuela the costs are assumed to be similar to Colombia, the capacities are determined using relevant export data. For the USA, both cost and capacity data are taken from Baruya (2007) as well as the Chinese port handling costs. Chinese port capacities are provided by the National Bureau of Statistics of China (2007). The costs for Poland are taken from Ritschel and Schiffer (2007) and the capacity is based on export data.

The Chinese political export restriction that is introduced in Section 3.7 is assigned to the Chinese exporter. For 2006 we use a value close to the actual exports of 59 million tons (Mt). In 2007 this quota was 70 Mt and dropped further to 47.7 Mt in 2008 and was likely not higher than 45 Mt in 2009.[13] Forecasting the level of future export licenses is difficult, and there are no such projections available. For the base case we assume the following values: 2006, 60 Mt; 2010: 60 Mt; 2015: 80 Mt; 2020: 90 Mt; 2025: 100 Mt; 2030, 110 Mt; 2035: 120 Mt and 2040: 130 Mt.

In sum the cost of a ton of exported coal adds up from production costs, land transport costs and the export fee. This is shown in Figure 8 for each exporter. In this figure, we also include the range of production costs in the respective production area. This range is represented by a white bar in the figure; it is calculated by subtracting the lowest average costs from the highest average costs.

4.5 Freight rates

Freight rates result from the supply-demand equilibrium in the dry bulk carrier market and have been very volatile in the past.[14] In general, the freight market behaves cyclically. This makes it difficult to predict future freight rates, which we

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Method of Transportation

[12] Spreadsheet *Railway Freight on Coal in India*

[13] Source: China Daily website

[14] Dry bulks include commodities such as iron ore, coal or grain.

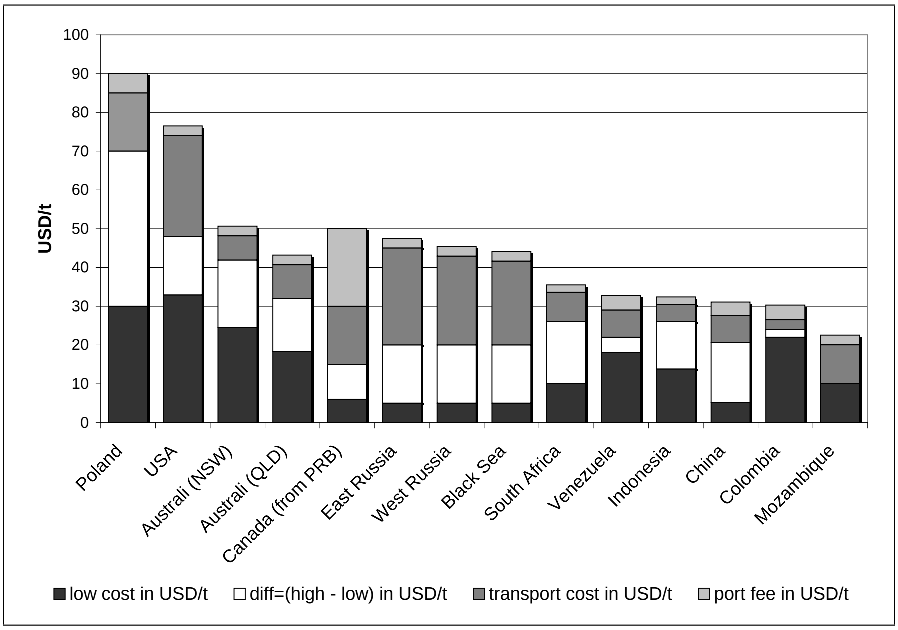

Figure 8: FOB costs for all export countries implemented into COALMOD-World (Source: own work based on Baruya, 2007; Ritschel and Schiffer, 2007; National Bureau of Statistics of China, 2007)

need as transportation cost input for the model. For the same route there is also a difference between Capesize and more expensive Panamax freight rates. The capacity of Capesize ships is higher but Panamax vessels are used more often on shorter routes. In the model, we assume the freight rate (transport cost) to be dependent on distance to reflect the spatial character of the international coal market. Given historical information on weekly freight rates on all available routes, we specify a linear regression using distance as explanatory variable.[15] The model transport costs between every export node and every import node with import possibility are calculated for 2006 using this equation by plugging in the corresponding distance x.[16] In 2006, the freight rates were below their average values between 2002 and 2009. The regression equation obtained for the average between 2002 and 2009 is $y = 0.0014x + 13.97$. The computed values y are used as model transport costs which are set to be constant from 2010 until 2040. Figure 9 depicts the regression results of the freight rate data points in dependency on distance. Moreover, Table 2 gives exemplary freight rates for some main routes. e.g. from South Africa (Richards Bay) to Northern Europe (Rotterdam).

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[15] Sources for weekly freight rates are McCloskey and Platts newsletters 2002-2009.

[16] Distance calculated using the *PortWorld* online distance calculator, `http://www.portworld.com/map/`

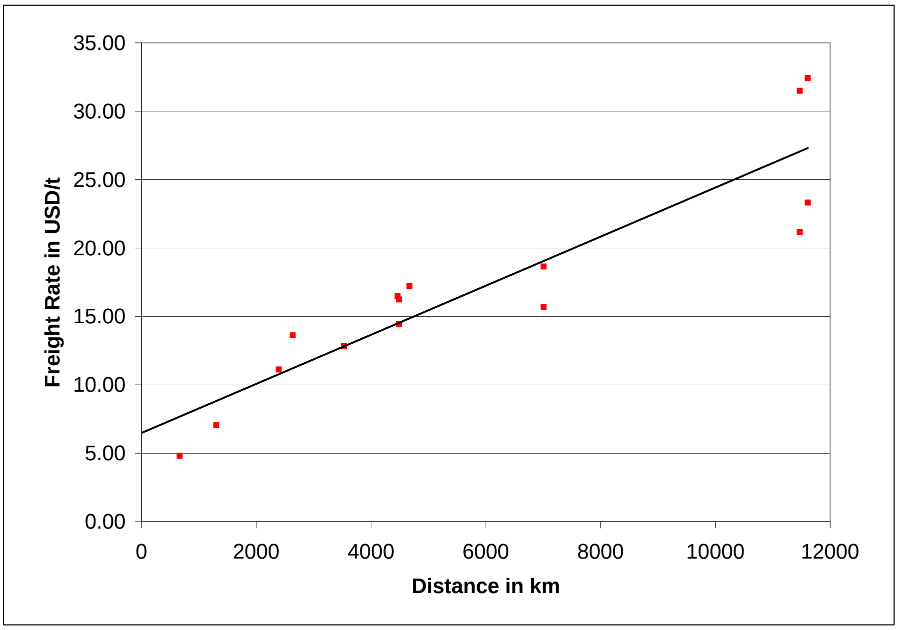

Figure 9: Linear regression of average freight rates between 2002 and 2009 (Source: own work based on Platts newsletters 2002-2009)

4.6 Demand

For the specification of the demand function of each consumption node, we need the "reference" price and "reference" quantity data for each model year. In order to have a consistent demand database for all countries in the model we use primarily data from the International Energy Agency (especially IEA, 2008a,b,c). The IEA data is expressed both in mass and energy units and thus fits the purpose of our modeling work since we model demand in energy values (Petajoules). However, the IEA data is on a very aggregated level, so the demand projections of the IEA (2008c) reference scenario must be allocated to the model's demand nodes. To achieve this, we take a bottom-up approach based on national data and ensure consistency by checking with the IEA data.

- For *Japan, Korea, the EU countries, Turkey, Israel, Ukraine, Kazakhstan, Morocco and the other Asian countries*, IEA data was used to determine the relevant quantities, either directly or as a share in a world subregion. For *Spain, Germany and the UK* we model only import demand by subtracting the local production from demand. For the demand projection we assume that the production in these countries drops by half in 2010 and stops in 2015. Price data was taken from the IEA and regional/national data.
- *Canada*: the quantity data for 2006 is based on Statistics Canada (2009) and the distribution for the future is based on the share of Canada in the OECD

Table 2: Freight rates for selected routes in USD/t (Source: own work based on Platts newsletters 2002-2009)

	From	**Australia-Queensland**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	27.06	30.05
C_JPN	**Japan**	12.81	18.92

	From	**Australia-New South Wales**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	27.41	30.32
C_KOR	**Korea**	14.49	20.22

	From	**Colombia-Puerto Bolivar**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	14.6	20.31

	From	**South Africa Richards Bay**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	19.08	23.82

	From	**Canada Vancouver**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	22.36	26.38
C_JPN	**Japan**	13.96	19.81

	From	**USA Hampton Roads (VA)**	
To		**2006**	**2010 - 2030**
C_NFB	**Rotterdam**	12.79	18.9

North America region. Price data was not available and was estimated using U.S. FOB price data.

- *USA*: the quantity data for 2006 is based on Energy Information Administration (2008, Table 26) and this repartition is used to estimate the future share of the U.S. model consumers in the USA projection. The prices are based on Energy Information Administration (2008, Table 34), converted to USD/GJ.

- *Russia*: the quantity data is based on Energy Forecasting Agency (2008) which provides data on installed and projected capacities for coal-fired power plants with detailed geographic coverage. Assuming a capacity factor of 80% and an average thermal efficiency of 35% (Crocker and Kovalchuk, 2008, p. 30) we get similar coal consumption levels expressed in energy units as the IEA. The regional breakdown is used to determine the shares of projected Russian demand of the two demand nodes. Inland price data was not found and is estimated using relevant cost and export price data.

- *China*: to get a regional breakdown of the IEA data for 2006 and the future to the model consumers, Chinese provinces' coal consumption data from the

Table 3: World Energy Outlook demand projections for coal for power generation in the reference scenario converted to Petajoules (Source: own work based on IEA, 2008c)

Region	**2006**	**2015**	**2020**	**2025**	**2030**
World	86876	115765	126148	135108	141305
OECD North America	22064	23823	24032	24325	24283
U.S.	20808	22190	22316	22734	22902
OECD Pacific	6406	7159	7243	7076	6783
Japan	2554	2638	2680	2512	2345
OECD Europe	10132	11053	10844	10341	9546
EU	10341	10718	10341	9713	8792
Eurasia	6322	7578	7746	8081	8332
Russia	3433	4731	5066	5485	5736
Non OECD Asia	38812	61462	71176	79633	86625
China	28973	47562	54554	59788	63388
India	6950	9546	11514	14068	17040
Middle East	335	502	670	837	1005
Africa	2512	3182	3349	3391	3224
Latin America	377	963	1172	1382	1507

National Bureau of Statistics of China (2007) was used. Price data is based on the China Coal Transportation and Distribution Association's (CCTD) database.

- *India*: The quantity data is based on Datanet India (2009) and is consistent with the IEA data. The consumption values of India's demand nodes for 2006 was used to allocate the IEA projection for India proportionally. The price data is determined using data from the Indian Ministry of Coal (2005, p. 58) that estimates the Indian delivered steam coal price to be between 12 and 16 USD per million kcal for distances between 1000 and 2000 kilometers.

- *South Africa*: the quantity data is based on the IEA (2008a) for 2006 and the share of South Africa in the region Africa is used to estimate future demand. The local price is determined using the value of local sales in 2006 divided by the volume of sales.[17] This gives an average price of 13.69 USD per ton that is converted to USD per Gigajoules using the relevant quality factor.[18]

There are only a few studies that incorporate long term price forecasts for coal. EWI/Prognos (2005) forecast quasi constant prices from 2010 until 2030 at approximately 1.5 Euro(2000)/GJ (p. XX). A more recent study by the European

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[17] Chamber of Mines of South Africa (2008, p. 18). Conversion done using average historical exchange rate for 2006 provided by `http://www.oanda.com/convert/fxhistory`

[18] The quality of the coal sold to the local market is very low with about 19 GJ/t, therefore the price per ton is low, too.

Commission (2008) forecasts a price decrease in 2010 in comparison to 2005 and then a continuous but slow increase until 2030 (p. 11). The assumption that prices in 2010 are lower than in 2005 can not realistically be made given the recent development of prices. Hence, in our data base we set the 2010 prices at the same level as 2006 and then increase all prices by 0.2% every five years, which is congruent with the price growth forecasted by the study of the European Commission (2008).

As shown in Section 3.5, own-price elasticities of coal demand are part of our demand curve definition. However, empirical research on elasticities, especially for coal, is scarce and the results are often not very satisfying. Dahl (1993) estimates short run elasticities to be between -0.55 and -0.3. Aune et al. (2001) use a value of -0.19 for the short run elasticity of coal demand in their model. The most recent study by Liu (2004) yields a rather peculiar result of a zero elasticity that is, of course, of rather limited use for defining demand functions for the model. We conclude that the price elasticity of coal demand is rather inelastic and assign elasticities ε_c of -0.1, -0.2 or -0.3 to the model consumers based on the percentage of coal use in the total power generation. The more dependent a country is on steam coal use in its electricity sector, the less elastic demand is assumed to be.

4.7 Investments

The investment costs are a major input to the multi-period model since they determine the future investment decisions. For the value-added chain from production to the export terminal, the IEA estimates investments costs of 50 USD (2007) per ton of annual capacity addition (USD/tpa) and for some new projects this number goes up as high as 80 USD/tpa (IEA, 2008c, p. 136). Rademacher (2008) finds average investment costs of 62 USD/tpa with a wide range from 15 USD/tpa for some Australian opencast mines to 130 USD/tpa for new underground mines in Ukraine and Mozambique (p. 75). But investment costs in Australia can also exceed 100 USD/tpa if the project includes new transport and washing facilities. We therefore assign values from 40 to 80 USD/tpa to the the different producers' investment costs in production capacity based on informations about the country and the prevalent type of mining.[19] Unit investment costs and the production capacity for the base year and every production node are shown in Figure 10.

Investments in additional overland transport capacity are set in a range between 10 and 55 USD/tpa depending on distance, landscape/relief and if the project is mostly greenfield or not. Investment costs for additional export capacity are set

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[19] The assignment is based on factors such as the prevalent type of mining, geology and the state of technology.

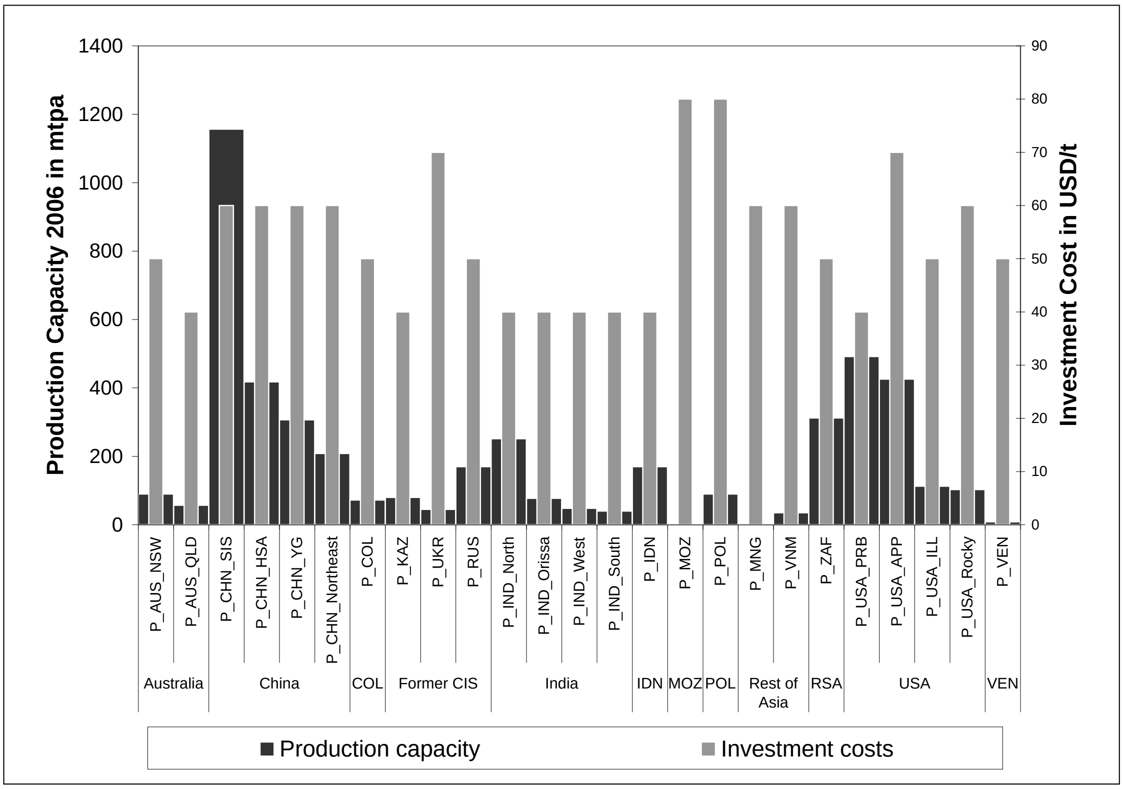

Figure 10: Capacity and investment costs for all production nodes in the base year (Source: own work based on IEA, 2008c; Rademacher, 2008)

between 10 and 30 USD/tpa depending on the country and the preexisting infrastructure. Figure 11 shows the unit costs of expanding export capacity together with the exporting harbor capacity in the base year.

Another important parameter for a multi-period model is the discount rate that is applied to the profit functions of the producers and exporters. We use the costs of capital to determine the discount rate. The database of A. Damodaran at the New York University's Stern Business School provides estimates of the costs of capital. For the coal industry, using data from 18 U.S. coal companies including major ones like *Peabody*, *Massey Energy* or *Arch coal*, he reports an average cost of capital of 10.3%.[20] For the model, a discount rate of 10% is used for both producers and exporters.

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[20] Website `http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.htm`, accessed on January 27, 2010.

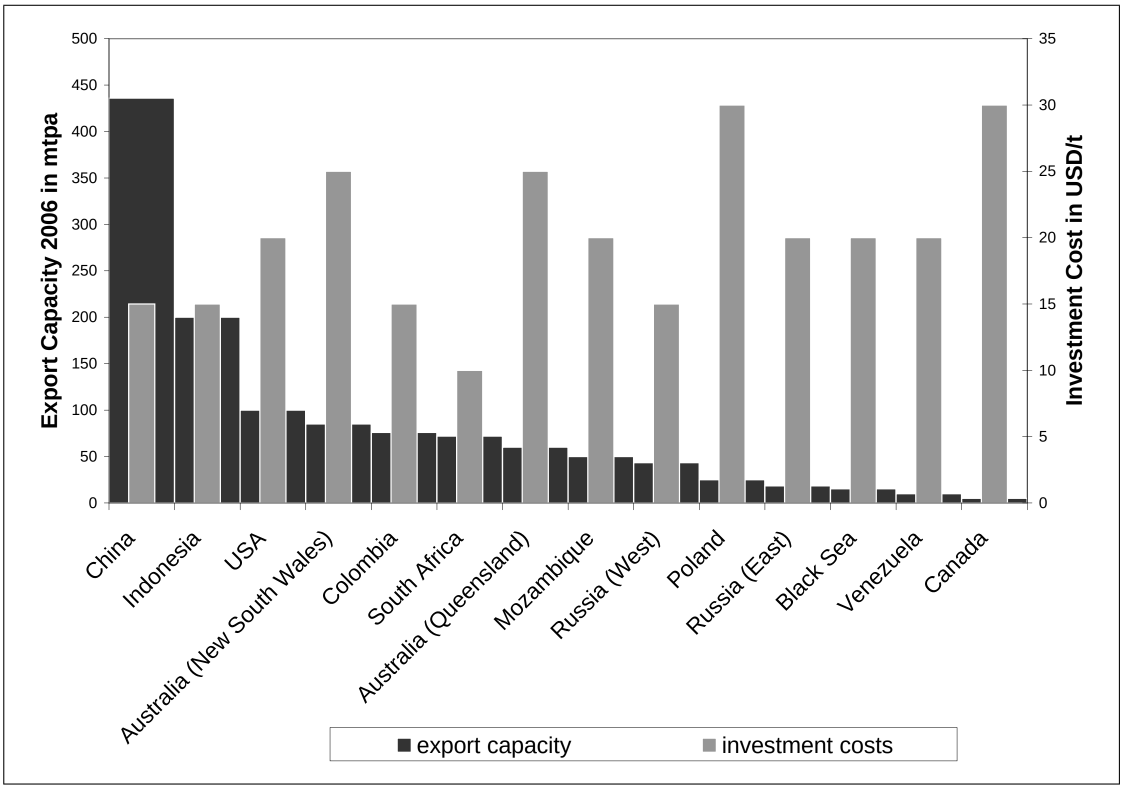

Figure 11: Capacity and investment costs for all export nodes in the base year (Source: own work based on IEA, 2008b; Rademacher, 2008)

5 Base Case Results

5.1 Base case assumptions

For each model year, the COALMOD-World model delivers results for the inland and seaborne trade flows, the prices, the level of investments and the value of the dual variables of the constraints that indicate if the constraint is binding and how strongly. The results of the last two model years 2035 and 2040 are not presented as there is a risk of distortion because there is less incentive to invest without any possible revenue after 2040. For convenience, we only present the results for the years 2006, 2010, 2020 and 2030 here.

Our results are based on the assumption of competitive and liberalized markets.[21] We also assume that the markets are fully integrated, that is, when a demand node can be reached by different producers or can import coal from overseas, it can fully substitute between the different sources. The base case results can be called "ideal" results, as they tell us how future demand should be served optimally and in

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[21] We are aware that not all countries currently have fully liberalized domestic markets (e.g. India and China). However we assume that the markets' structure or outcomes will move towards competitiveness in the future.

which countries investments should take place. We further assume that there is no politically motivated restriction except for the Chinese exports. The demand side of the model is based on the IEA's World Energy Outlook's reference scenario (IEA, 2008c), implying that there is no strong climate policy affecting steam coal demand.

We assume that there are restrictions on export capacity expansion because of technical and economic reasons. These restrictions are based on historical experience as well as on planned and forecasted expansions. They range from 5 to 30 mtpa of additional capacity over a 5 year period depending on the country. We do not impose restrictions on expansions of production capacity or inland transport capacity.

The model and base case presented here are a starting point for the implementation of scenarios. Restrictions on investments and sales could be imposed given the technical and political framework of specific countries. On the demand side stronger climate policies could be implemented. Given the number of parameters in the model there are plenty of possible scenarios that could be explored.

5.2 Global market results

The results for 2006 show a remarkable similarity with the actual observed trade pattern (see Appendix E for more details). We have a global integrated market with flows from Australia and Indonesia, two countries of the Pacific basin, to Europe in the Atlantic basin. The direction and relative amounts of the trade flows correspond to actual trade flows. This is an important achievement, given that we not only simulate the trade flows shown on the maps in Figures 12 to 15 but also simulate internal markets.[22] Modeling the interaction between imports and domestic supply is a difficult task and for demand nodes with these two sourcing possibilities we assume total substitutability. However, this may not always be the case; for example some power plants may be specifically designed for domestic coal or, conversely, some coastal power plants do not have the infrastructure to receive domestic coal.[23]

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[22] COALMOD-World is an energy-based model that calculates trade flows in Petajoules. For better representation, the results shown in Figures 12 to 15 are aggregated and expressed in million tons (Mt). These values are calculated using the relevant quality factors. Detailed flow results are reported in Appendix D.

[23] An optimal modeling exercise would require a database on a power plant level which is difficult to obtain, especially for countries like India or China. Nevertheless, the COALMOD-World model is specific enough to identify major trends and dynamics on the world market and the interaction with domestic markets.

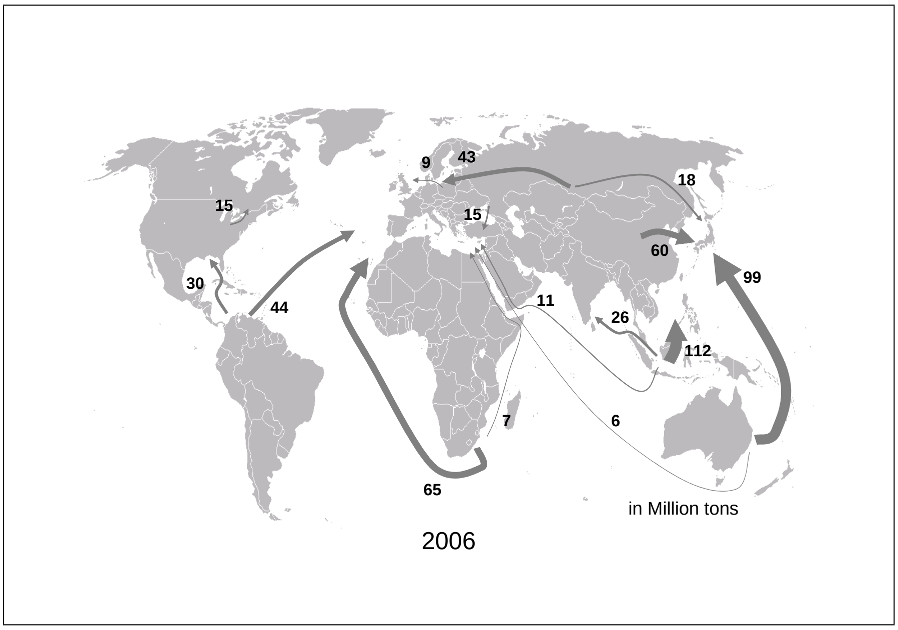

Figure 12: Global results 2006: seaborne trade flows (in Mt)

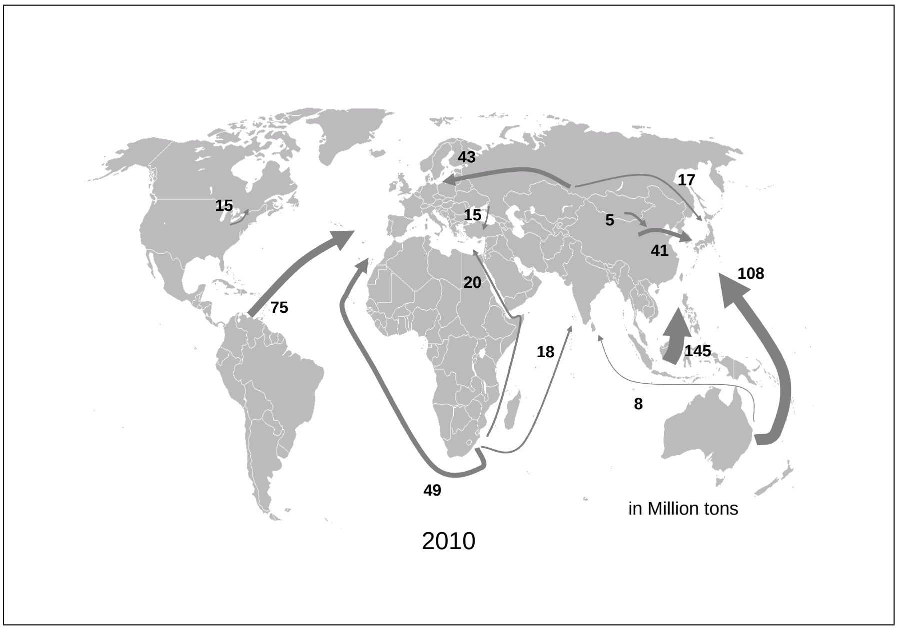

Figure 13: Global results 2010: seaborne trade flows (in Mt)

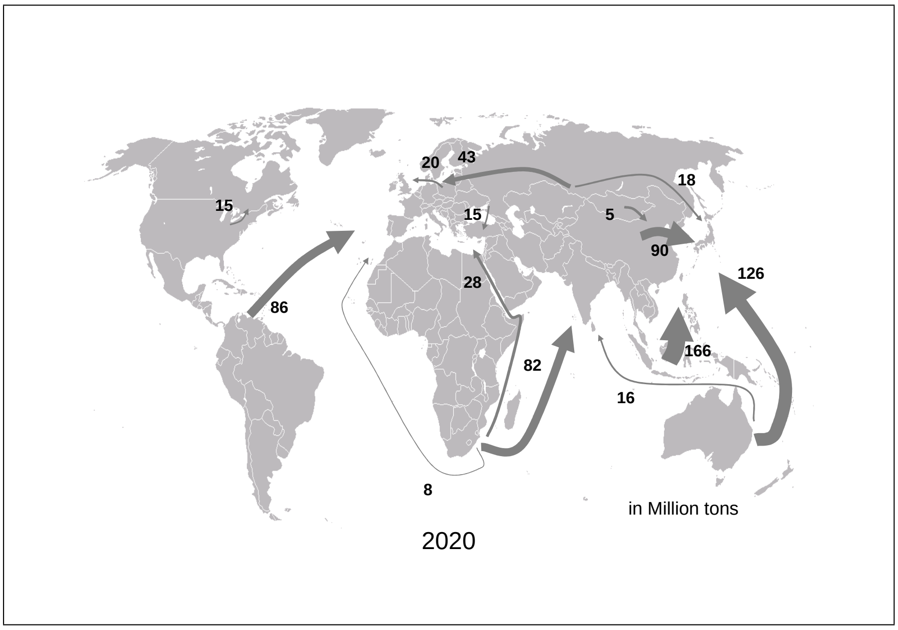

Figure 14: Global results 2020: seaborne trade flows (in Mt)

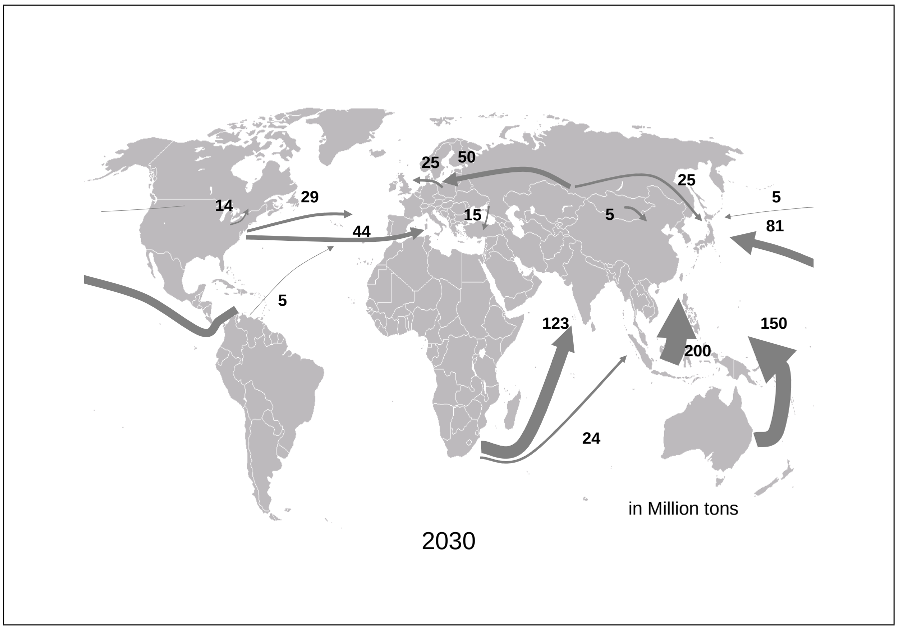

Figure 15: Global results 2030: seaborne trade flows (in Mt)

Australia and Indonesia remain key players in the Pacific market. Their exports increase by 50% and 25%, respectively, and reach the high levels of 150 mtpa for Australia in 2030 and 200 mtpa for Indonesia. Indonesia has been the most dynamic player in the past years, now with a higher export level than Australia. Our model confirms this trend for 2010 and forecasts that Indonesia consolidates its role as the leading steam coal exporter, before Australia. Low production costs and flexible, low cost investments are the main reasons for this development. However, in terms of growth of exports for the time period 2006 to 2030, Australia the a more dynamic player with an increase by 50%.

The third most important exporter is South Africa with an export level that doubles from 2006 till 2030. South Africa is also the producer with the most potential since the export capacity investment restriction of 15 mtpa over five years is constantly binding, meaning that South Africa would be willing to export significantly more steam coal. This is due to an increase in import demand in Asia and especially in India that opens new markets for the good quality South African coal. We can see the emergence of a third market (in addition to the traditional Atlantic and Pacific markets) that could be called Indian market and were South Africa would become the key player.

In the Atlantic market there are various players that supply Europe and the key players vary over time. After South Africa in 2006 and Colombia from 2010 to 2025, the U.S. become an important supplier to Europe in 2030, exporting nearly 73 Mt. Russia plays a relatively small role on the Atlantic market as well as on the Pacific market and concentrates on its domestic market. This is mostly due to the high transport cost to reach the export ports. However, both Russia and Poland increase their exports slightly until 2030.

China is a swing supplier on the world market with a high variability of exports, ranging from 0 Mt in 2030 to 99 Mt in 2025. The reason for this high variability is the interaction between the domestic supplies and the imports to Southern China that are multiplied by more than three to reach a level of 274 Mt in 2030. The political restrictions play a lesser role. When they are binding (like in 2020), the dual variable has a low value. Hence, removing these restrictions would not affect the exports significantly.

On a global perspective, the most significant result of our modeling exercise is the shifting of trade flows toward the Asian/Pacific markets which occurs in two marked steps. We start today with a global integrated market with trade flows from the Pacific market to the Atlantic market. Then, we notice a gradual shift eastwards until 2020 with flows from South Africa being directed towards Asia and especially India. Colombia replaces South Africa as the key supplier to Europe. The

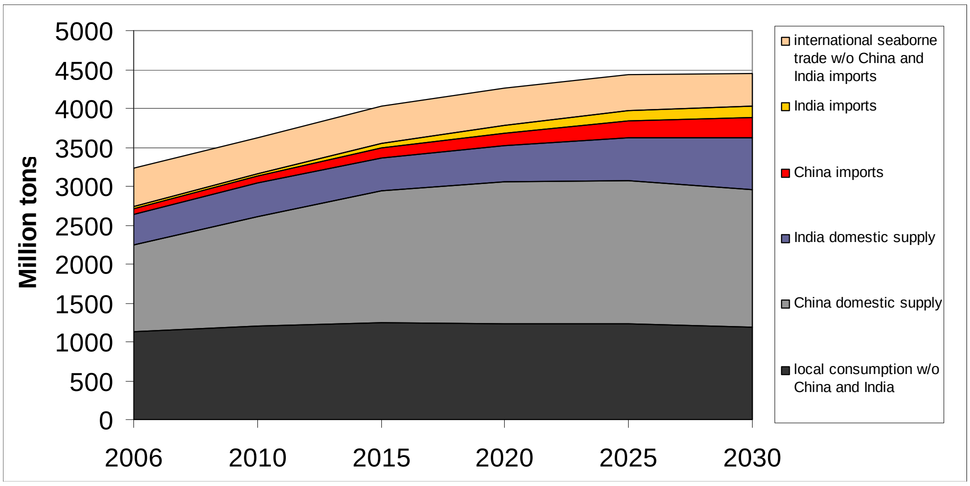

Figure 16: Global results: aggregated consumption and imports (in Mt)

second step in the shift occurs in 2030. We expect an additional shift westwards with Colombia delivering to Japan and Korea, resource poor countries with a high willingness to pay.[24] By then, the overall picture on the global market has significantly changed: the U.S., Russia and Poland are the only suppliers to Europe; South Africa, Europe's traditional supplier, has become a major supplier to India and the Pacific market; and Colombia also mainly becomes a Pacific market supplier. The Asian market is pulling supplies so strongly that, in 2030, we even observe trade flows to Japan from the Powder River basin in the Western U.S. (though only a small amount of 5 mtpa).

Figure 16 sets the trade results in relation to the locally produced and consumed quantities of steam coal as well as to the imports and local supply results for India and China. The total surface of this graph represents the total consumption and the different areas differentiate the consumption by its origin, seaborne trade or local supply with a special focus on India and China. Unsurprisingly, China's steam coal consumption represents the biggest share of 36% to 46% of the worldwide consumption in every model year. The volume of the international seaborne trade increases by 42% from 2006 to 2030 but its share in total consumption remains constant at around 18%. Also, China and India account for most of this trade increase as their imports are multiplied by 4.5 from 2006 to 2030. In 2030, the Chinese and Indian imports represent half of the international trade. Seaborne imports of other countries decrease by 15% during the same time.

The share of international seaborne trade in the global consumption have in-

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[24] There are no extra costs in the data for using canals like the Panama canal. It is not clear if such an inter-basin trade flow would prevail with the incorporation of this cost component. However, the current expansion of the Panama canal that will be completed in 2015 is thought to be facilitating Colombian exports to Asia

creased constantly since the 1990s until 2008 (IEA, 2010). However, our model results show a stabilization of this share in the future at around 18%. This is due to a stabilization or even decrease in demand of importing countries like EU countries or Japan and Korea. But the main driver for this development is the fact that coal-rich contries develop their own resources significantly. The U.S. do not import any more and India and China extend their production massively. As stated before, we do not impose restrictions on expansions of local resources, contrary to what we do for export.

Restrictions may affect the domestic market and world market significantly and may be assessed in scenario analyses. For example, a revival of the U.S. exports to Europe in 2030 could be threatened by environmental regulation, expressed by a substantial increase in production costs and probably a reduction in available reserves in the Appalachia region because of a possible ban of the mountain top removal mining technique.[25] This would mean that Europe would be faced with a similar situation as in the natural gas market with Russia as the dominant supplier, or it should be willing to pay more to buy coal from other suppliers.

The Chinese coal industry is in a process of a difficult restructuring. The small, dangerous and often illegal township and village enterprise (TVE) mines have to be closed to make room for more efficient firms (Minchener, 2007). However, the reliance of China on these TVE for its coal supply is heavy. Closing them too fast or a slow restructuring process could increase the need for coal imports. The same is true for India where the reform process from state run enterprises to efficient firms is even more cumbersome (Carl et al., 2008). The increase in Indian production capacity might also be limited by political and technical factors.

5.3 Price results

Figure 17 shows the price development of some major regions. Globally, prices show an upward trend over the time period 2006 to 2030. The lowest prices with the lowest increase over time are the domestic prices in South Africa, the U.S. and Russia. These demand nodes are close to large and cheap sources of supply and are not connected to, and thus almost not affected by, the global market. However, we can see that for the Russia-Central and the U.S. domestic prices the increase in 2030 is higher that in the years before. This is due to the increased exports to Europe in that year. The highest prices are the import prices in Europe, the Mediterranean

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[25] Mountaintop removal mining (MTR), sometimes referred to as mountaintop mining (MTM), is a form of surface mining that involves the mining of the summit or summit ridge of a mountain. The process involves blasting with explosives to remove up to 300 m of mountain to expose underlying coal seams.

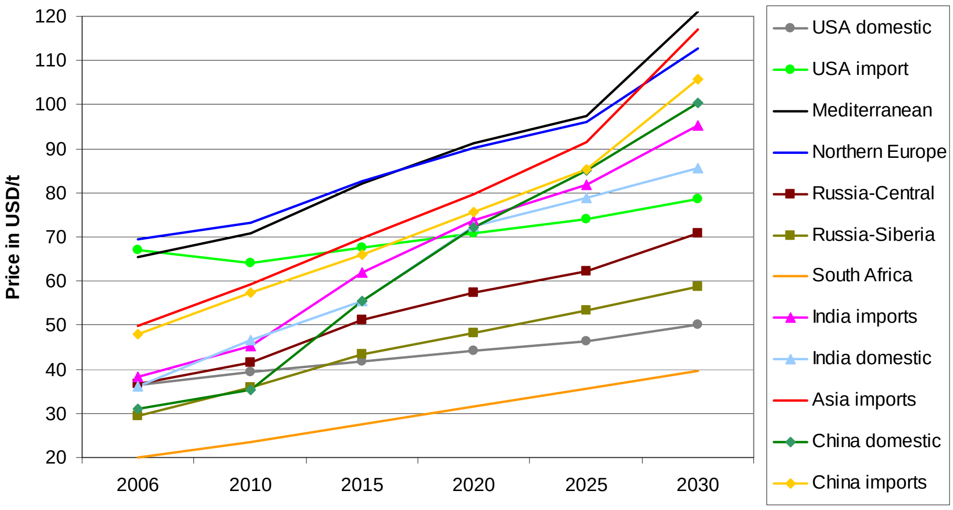

Figure 17: Global results: average prices of selected regions for all model years (in USD/t)

countries and Asia due to the transport cost and the lack of own resources in the importing countries. The highest increase over time can be seen in the Indian and Chinese prices, both domestic and import. This is due to an increased integration in the world market through increased imports.

Our U.S. price results are in the same range as the latest available forecasts from the Annual Energy Outlook (EIA, 2010). Their projected delivered prices for the period 2008 to 2030 are fairly stable, ranging from 30.31 USD/t to 40.44 USD/t (in 2008 dollars). Our domestic U.S. price results are between 36.39 USD/t and 50.06 USD/t and they also include the transport costs. Thus, our model prices largely conforms to the EIA projections. Unfortunately, similar price projections are not available for other countries to perform the same check on prices. It is important to note that the imports prices represent the prices at the Gulf node of the U.S. But the U.S. import coal only in 2006 in our model. Thus, this price also represents a domestic price for the subsequent years.

Predicting prices is a difficult undertaking and a steep increase in prices like we have seen in the coal market in 2007 and 2008 should not give the false impression that prices will stay or be high in the future. Our model cannot predict short-term price volatility[26] but gives long-term price trends based on the fundamentals of the market. The same goes for costs, as discussed in Section 4.2, to which the prices are closely linked in a competitive market. To place the discussion of future price/costs in a historical long-term context, one can look at the real prices and productivity

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[26] Short term volatility can be caused by extreme weather events, strikes, infrastructure problems etc. on the supply side. On the demand side we can consider shocks that come from the energy system like short-term problems with nuclear reactors or low water level of hydro-power plants.

of U.S. subsurface mining between 1949 and 1994 in Figure 18. One sees that the real price is closely tied to the productivity measured in output per hour. While cost drivers on the coal market such as prices of oil or equipment are uncertain and may rise, one must not underestimate the effect of productivity increases that can easily outweigh them. Thus, slowly increasing prices in real terms as computed by the EIA for the U.S. and by the COALMOD-World model for the entire world are realistic.

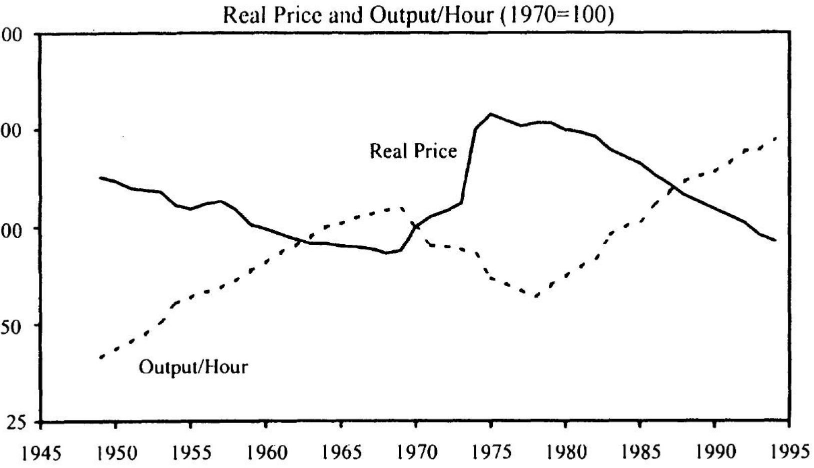

Figure 18: U.S. mining real price and productivity from 1949 to 1994, (Source: Prescott, 1998, p. 545)

6 Conclusions

In this paper, we have presented a tool of analysis for the future global steam coal market, the "COALMOD-World" model. We have shown how we can model this market and its future developments using a large scale equilibrium model that relies on microeconomics and game theory. The combination of model theory and detailed market analysis provides the ground for the development and the implementation of the model. The modeling framework used is the mixed complementarity (MCP) format.

The model results show that the international steam coal trade will continue to grow. The projected growth of 42% between 2006 and 2030 is mainly driven by fast growing economies like India and China that will multiply the volume of their imports by 4.5. Imports from other countries will decline by 15% during the same time. This will increase competition between importing countries to secure steam coal supplies.

In some producing countries today there are discussions about restricting exports, for example to protect the local demand for coal. However, our model results suggest that it would be beneficial for the producers not to restrict their exports. This is especially true for Indonesia, China and South Africa that are major suppliers to the international steam coal market. A future revival of the U.S. as a major exporter is threatened by environmental regulations, especially a possible ban on mountaintop removal mining. The projected importance of these suppliers shows that such political restrictions could have a great potential to affect the international steam coal market and must thus be watched carefully in the near future. This type of coal market policies could be explored with the model in a next step. Also, restrictions on investment in production capacities in major markets could have a significant effect on global trade and increase the import dependency of India and southern China.

Another important aspect for the future of coal markets is climate change and climate policies. Coal is considered by many to be the number one climate enemy. If more restrictions on emissions than in the IEA (2008c) World Energy Outlook's reference case were imposed, there would be a direct effect on electricity generation from coal. In the near future global trade growth would be smaller because the main importing developed countries like the EU or Japan are more likely to curb their coal consumption than India or China. However, the successful implementation of carbon capture and storage for coal-fired power plants might change this reality after 2020. Such a development would make coal attractive again for the developed countries with ambitious emissions reduction goals that could also afford such technologies. This would boost global trade but also increase competition between importers on a potentially supply constrained market. The COALMOD-World model can be used for the implementation of a wide range of scenario model runs to investigate the interaction of the national and international steam coal markets under various energy and climate policy scenarios until 2030.

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Appendix A: Mathematical Formulation of the Model

The profit maximization problem described in 3.2 to 3.7 has the following Karush-Kuhn-Tucker conditions (KKTs) of optimality that are obtained after deriving the Lagrangian function of each player type with respect to their decision variables and dual variables of constraints.

- Producers KKTs:

$$\begin{aligned} 0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot \Big[&- p_{ac} \\ &+ \frac{\partial C^P_{af}}{\partial x_{afc}} + trans\_c_{afc} \cdot \kappa_{af} \Big] \\ &+ \alpha^P_{af} \cdot \kappa_{af} + \frac{5}{2} \cdot \alpha^{Res}_f \cdot \kappa_{af} + \alpha^{Tcap\_c}_{afc} \cdot \kappa_{af} \perp x_{afc} \geq 0 \end{aligned} \tag{25}$$

$$\begin{aligned} 0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot \Big[&- p_{ae} \\ &+ \frac{\partial C^P_{af}}{\partial y_{afe}} + trans\_e_{afe} \cdot \kappa_{af} \Big] \\ &+ \alpha^P_{af} \cdot \kappa_{af} + \frac{5}{2} \cdot \alpha^{Res}_f \cdot \kappa_{af} + \alpha^{Tcap\_e}_{afe} \cdot \kappa_{af} \perp y_{afe} \geq 0 \end{aligned} \tag{26}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot CPinv_{af} - \sum_{a'>a} \alpha^P_{af} + \alpha^{Pinv}_{af} \perp Pinv_{af} \geq 0 \tag{27}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot CTinv\_c_{afc} - \sum_{a'>a} \alpha^{Tcap\_c}_{afc} + \alpha^{Tinv\_c}_{afc} \perp Tinv\_c_{afc} \geq 0 \tag{28}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^a \cdot CTinv\_e_{afe} - \sum_{a'>a} \alpha^{Tcap\_e}_{afe} + \alpha^{Tinv\_e}_{afe} \perp Tinv\_e_{afe} \geq 0 \tag{29}$$

$$0 \leq Pcap_f + \sum_{a'<a} Pinv_{af} - \left(\sum_c x_{afc} \cdot \kappa_{af} + \sum_e y_{afe} \cdot \kappa_{af} \right) \perp \alpha_{af}^{P} \geq 0 \tag{30}$$

$$0 \leq Pmaxinv_{af} - Pinv_{af} \perp \alpha_{af}^{Pinv} \geq 0 \tag{31}$$

$$\begin{aligned} 0 \leq & Res_f - \sum_{a \in A} \Big[\Big(\sum_c x_{afc} \cdot \kappa_{af} + \sum_e y_{afe} \cdot \kappa_{af} \\ & + \sum_c x_{(a-1)fc} \cdot \kappa_{(a-1)f} + \sum_e y_{(a-1)fe} \cdot \kappa_{(a-1)f} \Big) * \frac{5}{2} \Big] \perp \alpha_f^{Res} \geq 0 \end{aligned} \tag{32}$$

$$0 \leq Tcap\_c_{fc} + \sum_{a'<a} Tinv\_c_{afc} - x_{afc} \cdot \kappa_{af} \perp \alpha_{afc}^{Tcap\_c} \geq 0 \tag{33}$$

$$0 \leq Tcap\_e_{fe} + \sum_{a'<a} Tinv\_e_{efc} - y_{afe} \cdot \kappa_{af} \perp \alpha_{afe}^{Tcap\_e} \geq 0 \tag{34}$$

$$0 \leq Tmaxinv\_c_{afc} - Tinv\_c_{afc} \perp \alpha_{afc}^{Tinv\_c} \geq 0 \tag{35}$$

$$0 \leq Tmaxinv\_e_{afe} - Tinv\_e_{afe} \perp \alpha_{afe}^{Tinv\_e} \geq 0 \tag{36}$$

$$\begin{aligned} 0 \leq & mc\_int_{af} = mc\_int_{(a-1)f} \\ & + mc\_slp_{(a-1)f} \cdot \left(\sum_c x_{(a-1)fc} \cdot \kappa_{(a-1)f} + \sum_e y_{(a-1)fe} \cdot \kappa_{(a-1)f} \right) \cdot mc\_int\_var_f \\ & , \quad mc\_int_{af} \text{ (free)} \end{aligned} \tag{37}$$

$$\begin{aligned} 0 \leq & mc\_slp_{af} = mc\_slp\_start_f + mc\_slp\_var_f \cdot \sum_{a'<a} Pinv_{a'f}, \\ & mc\_slp_{af} \text{ (free)} \end{aligned} \tag{38}$$

- Exporters KKTs:

$$
\begin{aligned}
0 \leq \left(\frac{1}{1+r_e}\right)^a \cdot \Big[&- p_{ac} \\
&+ p_{ae} + Cport_{ae} \cdot \kappa_{ae} + searate_{aec} \cdot \kappa_{ae} \Big] \\
&+ \mu^E_{ae} \cdot \kappa_{ae} \perp z_{aec} \geq 0
\end{aligned} \tag{39}
$$

$$
0 \leq \left(\frac{1}{1+r_e}\right)^a \cdot CEinv_{ae} - \sum_{a'>a} \mu^E_{ae} + \mu^{Einv}_{ae} + \mu^{Emax}_{e} \perp Einv_{ae} \geq 0 \tag{40}
$$

$$
0 \leq Ecap_e + \sum_{a'<a} Einv_{ae} - \sum_{c} z_{aec} \cdot \kappa_{ae} \perp \mu^E_{ae} \geq 0 \tag{41}
$$

$$
0 \leq Emaxinv_{ae} - Einv_{ae} \perp \mu^{Einv}_{ae} \geq 0 \tag{42}
$$

$$
0 \leq maxcap_e - Ecap_e - \sum_{a} Einv_{ae} \perp \mu^{Emax}_{e} \geq 0 \tag{43}
$$

- Producers Quality Factor:

$$
\kappa_{af} = \kappa_f + \delta_f \cdot \sum_{a' \leq a} \left(\sum_{c} x_{afc} + \sum_{e} y_{afe} \right) \quad , \kappa_{af} \text{ (free)} \tag{44}
$$

- Final Demand Equation:

$$
p_{ac} - p_{ac} \left(\sum_{f} x_{afc}, \sum_{e} z_{aec} \right) = 0 \quad , p_{ac} \text{ (free)} \tag{45}
$$

- Market Clearing Condition:

$$
0 = y_{afe} - \sum_{c} z_{aec} \quad , p_{ae} \text{ (free)} \tag{46}
$$

- Chinese Export Restriction:

$$0 \leq China\_lic_{a\,E_{CHN}} - \sum_{NoChina(c)} z_{aec} \cdot \kappa_{ae} \perp \pi_{a\,E_{CHN}} \geq 0 \tag{47}$$

The KKT (Karush Kuhn Tucker) optimality conditions of each model player and the additional final demand, market clearing and quality equations form a mathematical equilibrium problem in the MCP format. This model is programmed in GAMS and it is solved using the PATH solver (Ferris and Munson, 2000).

Appendix B: Nodes of COALMOD-World

Table 4: Nodes of the COALMOD-World Model

Country	Producers		Exporters		Consumers		Port
Canada					C_CAN	Ontario	No
USA	P_USA_PRB	Powder River Basin	E_CAN	Vancouver	C_USA_Rocky		No
	P_USA_APP	Appalachian	E_USA_East	Hampton Roads	C_USA_East		Boston
	P_USA_Rocky	Rocky Mountains			C_USA_Central		No
	P_USA_ILL	Illinois Basin			C_USA_South		No
					C_USA_Gulf		Mobile
Colombia	P_COL		E_COL	Puerto Bolivar			
Venezuela	P_VEN		E_VEN	Maracaibo			
Morocco					C_MAR		Mohammedia
Portugal					C_PRT		Sines
Spain					C_ESP		Gijon
UK					C_GBR		Immingham
NL_F_BEL					C_NFB	Netherlands, France, Belgium	Rotterdam
Germany					C_DEU		Rotterdam
Denmark					C_DNK		Aabenraa
Finland					C_FIN		Kotka
Italy					C_ITA		Taranto
Poland	P_POL		E_POL	Gdansk	C_POL		No
Turkey					C_TUR		Mersin/Samsun
Israel					C_ISR		Ashdod
Eurasia	P_RUS	Kemerovo/Kuznets	E_RUS_West	Baltic/Riga	C_RUS_Sibiria		No
			E_RUS_East	Vostochny	C_RUS_Central		No
			E_Black_Sea	Mariupol			
	P_UKR	Ukrainian/Russian Donets			C_UKR		No
	P_KAZ	Kazakhstan/Ekibastuz			C_KAZ		No
South Africa	P_ZAF		E_ZAF	Richards Bay	C_ZAF		No
Mozambique	P_MOZ		E_MOZ	Maputo			
India	P_IND_North	Chhattisgarh, Jharkhand, Madhya Pradesh, Uttar Pradesh, West Bengal			C_IND_East	Bihar, Jharkhand, West Bengal, Orissa, Chhattisgarh	No
	P_IND_Orissa	Orissa			C_IND_North	Delhi, Punjab, Rajasthan, Uttar Pradesh	No
	P_IND_West	Maharashtra			C_IND_West	Gujarat, Maharashtra, Madhya Pradesh	Mundra
	P_IND_South	Andhra Pradesh			C_IND_South	Andhra Pradesh, Tamil Nadu, Karnataka	Chennai
Thailand					C_THA		Bangkok
Malaysia					C_MYS		Lumut
Vietnam	P_VNM		E_VNM	Campha	C_VNM		No
Indonesia	P_IDN		E_IDN		C_IDN		No
China	P_CHN_SIS	Shanxi, Shaanxi, Inner Mongolia , Hebei	E_CHN	Qinhuangdao	C_CHN_SIS	Shanxi, Shaaxi, Inner Mongolia	No
	P_CHN_Northeast	Liaoning, Jilin , Heilongjiang			C_CHN_Northeast	Heilongjiang, Jilin, Liaoning	No
	P_CHN_HSA	Henan, Shandong, Jiangxi, Fujian, Jiangsu			C_CHN_Main	Beijing, Tianjin, Hebei, Henan, Shandong	No
	P_CHN_YG	Guizhou, Hunan, Chongqing , Sichuan			C_CHN_Eastern	Jiangsu, Hubei, Chongqing, Shanghai, Zhejiang	Shanghai/Ningbo
					C_CHN_South	Jiangxi, Guizhou, Sichuan, Guangdong, Fujian, Guangxi and Hunan	Guangzhou
Mongolia	P_MNG				C_MNG		No
Korea					C_KOR		Ulsan
Japan					C_JPN		Yokohama
Taiwan					C_TWN		Kaohsiung
Philippines					C_PHL		Pagbilao
Australia	P_AUS_QLD		E_AUS_QLD	Dalrymple Bay			
	P_AUS_NSW		E_AUS_NSW	Newcastle			

Appendix C: Data of COALMOD-World

Reference demand data

Table 5: Reference demand data for all consumption nodes and periods (Source: IEA, 2008a,c, and regional information (see Section 4.6))

Consumer node	**Price* in USD/GJ**	**Energy consumption in PJ**							
	2006	**2006**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
C_CAN	1.53	472	489	509	514	520	519	513	498
C_CHN_Eastern	1.74	5332	6852	8752	10039	11002	11665	11961	11777
C_CHN_Main	1.17	8635	11097	14175	16259	17819	18892	19373	19075
C_CHN_Northeast	1.31	3399	4368	5579	6400	7014	7436	7625	7508
C_CHN_SIS	0.92	5734	7370	9414	10797	11833	12546	12865	12667
C_CHN_South	1.93	5873	7548	9641	11059	12120	12849	13176	12973
C_DEU	2.64	874	890	909	877	823	745	678	509
C_DNK	2.74	223	227	232	223	210	190	173	130
C_ESP	2.35	484	492	503	485	456	412	375	281
C_FIN	3.13	249	254	259	250	235	212	193	145
C_GBR	2.64	1325	1348	1377	1328	1248	1129	1028	771
C_IDN	0.69	610	768	965	1118	1251	1361	1414	1571
C_IND_East	1.44	1950	2180	2568	3097	3784	4584	5614	6721
C_IND_North	2.02	2508	2804	3303	3983	4867	5895	7220	8644
C_IND_South	2.69	1420	1587	1870	2255	2755	3337	4087	4893
C_IND_West	2.69	1371	1533	1806	2178	2661	3223	3948	4726
C_ISR	3.47	334	408	501	668	835	1002	1197	1446
C_ITA	2.81	481	489	500	482	453	410	373	280
C_JPN	2.45	2554	2591	2638	2680	2512	2345	2100	1800
C_KAZ	0.69	988	1075	1184	1210	1262	1302	1281	1265
C_KOR	2.06	1583	1665	1769	1790	1748	1676	1556	1359
C_MAR	2.78	124	138	157	165	167	159	143	123
C_MNG	0.92	4	1	3	5	7	9	9	10
C_MYS	1.30	283	356	448	519	581	632	656	729
C_NFB	3.24	580	591	603	582	547	495	450	338
C_PHL	1.38	170	214	269	312	349	379	394	438
C_POL	2.38	1712	1742	1779	1716	1612	1459	1328	996
C_PRT	2.28	138	140	143	138	130	117	107	80
C_RUS_Central	1.10	1307	1526	1800	1928	2087	2183	2245	2245
C_RUS_Siberia	0.83	2127	2484	2931	3138	3397	3553	3655	3655
C_THA	1.52	142	179	225	260	291	317	329	366
C_TUR	2.96	475	494	518	508	485	447	389	314
C_TWN	2.49	1287	1620	2037	2359	2640	2872	2984	3315
C_UKR	1.24	756	823	906	926	966	997	981	969
C_USA_Central	0.92	7682	7909	8192	8239	8393	8455	8418	8381
C_USA_East	1.92	1600	1647	1706	1715	1748	1760	1753	1745
C_USA_Gulf	1.70	6275	6460	6691	6729	6855	6906	6875	6845
C_USA_Rocky	0.84	2443	2516	2606	2620	2670	2689	2677	2666
C_USA_South	1.70	2808	2891	2995	3012	3068	3091	3077	3064
C_VNM	0.69	97	122	153	177	198	216	224	249
C_ZAF	0.72	2359	2639	2988	3146	3185	3028	2724	2348
*Prices increase constantly by 0.2% in every 5-year-period.									

Table 6: **Production cost curve parameters** for all producers (Source: own work based on Platts newsletters 2002-2009, Baruya, 2007; Rademacher, 2008; Energy Information Administration, 2008; National Bureau of Statistics of China, 2007; New South Wales Department of Primary Industries, 2009; Queensland Department of Mines and Energy, 2009; Datanet India, 2009; Ritschel and Schiffer, 2005; Geological Survey of India, 2008)

	Data for 2006				Model Endogenous Results for 2030			
Production nodes	Intercept b in USD/t	Slope a in USD/(t·t)	Production capacity	Marg. costs at production cap.	Intercept b in USD/t	Slope a in USD/(t·t)	Production capacity	Marg. costs at production cap.
P_USA_PRB	6.00	0.02	491.62	15.00	10.77	0.0200	491.62	20.60
P_USA_Rocky	21.00	0.09	102.64	30.00	23.01	0.0900	102.64	32.25
P_USA_ILL	25.20	0.09	112.89	35.00	35.36	0.0900	112.89	45.52
P_USA_APP	32.90	0.04	425.69	48.00	51.19	0.0400	425.69	68.21
P_COL	22.00	0.03	72.30	24.00	24.10	0.0289	83.30	26.51
P_VEN	18.00	0.47	8.60	22.00	27.36	0.4840	10.00	32.20
P_POL	30.00	0.44	90.00	70.00	36.87	0.4400	90.00	76.47
P_UKR	10.00	0.36	45	26.00	33.77	0.3600	45.00	49.97
P_KAZ	5.00	0.13	80	15.00	14.94	0.1300	80.00	25.34
P_RUS	5.00	0.09	170	20.00	12.59	0.0900	170.00	27.89
P_ZAF	10.00	0.05	311.96	26.00	25.29	0.0500	311.96	40.89
P_IND_North	7.53	0.11	251.71	36.00	14.67	0.0944	491.15	61.02
P_IND_Orissa	4.50	0.14	77.33	15.00	7.52	0.1400	100.00	21.52
P_IND_West	12.40	0.28	48.00	26.00	16.74	0.2800	84.47	40.39
P_IND_South	12.00	0.50	40.16	32.00	17.02	0.5000	53.55	43.79
P_VNM	10.00	0.43	35	25.00	21.73	0.4300	35.00	36.78
P_IDN	13.80	0.07	170	26.00	20.18	0.0674	222.72	35.19
P_CHN_SIS	5.20	0.03	1156.55	36.00	20.18	0.0300	1156.55	54.88
P_CHN_Northeast	15.00	0.05	208.56	25.00	25.00	0.0500	237.54	36.87
P_CHN_HSA	20.00	0.04	417.72	36.00	31.28	0.0400	417.72	47.99
P_CHN_YG	20.00	0.05	306.55	36.00	30.68	0.0800	306.55	55.20
P_AUS_QLD	18.30	0.24	57.07	32.00	25.15	0.2340	60.09	39.21
P_AUS_NSW	24.50	0.19	89.95	41.90	31.48	0.1900	89.95	48.57
P_MNG	5.20	0.01	2.2	5.22	13.13	0.2401	25.21	19.19
P_MOZ	10.00	0.05	1	10.05	10.97	0.1633	12.33	12.99

N.B.: The cost curve has the form $mc = a \cdot x + b$, where a is the intercept and b the slope of the marginal cost curve mc.

Table 7: Data and assumptions for the endogenous cost mechanism

Country	**Model Producers**	**Mining Basin Type**	**Intercept Increase**	*mc_slp_var_f*	$mc\_int\_var_f$
USA	P_USA_PRB	2	slow	$-1 \cdot 10^{-5}$	0.1
	P_USA_Rocky	2	slow	$-1 \cdot 10^{-5}$	0.1
	P_USA_ILL	3	moderate	0	0.2
	P_USA_APP	3	high	0	0.4
Colombia	P_COL	2	slow	$-1 \cdot 10^{-4}$	0.2
Venezuela	P_VEN	1	high	$1 \cdot 10^{-2}$	0.4
Poland	P_POL	3	slow	0	0.1
Ukraine	P_UKR	3	moderate	0	0.4
Kazakhstan	P_KAZ	2	moderate	$-1 \cdot 10^{-3}$	0.2
Russia	P_RUS	2	slow	$-2 \cdot 10^{-4}$	0.1
South Africa	P_ZAF	3	moderate	0	0.3
India	P_IND_North	2	moderate	$-1 \cdot 10^{-4}$	0.05
	P_IND_Orissa	3	moderate	0	0.1
	P_IND_West	3	moderate	0	0.05
	P_IND_South	3	moderate	0	0.05
Vietnam	P_VNM	4	high	$1 \cdot 10^{-2}$	0.6
Indonesia	P_IDN	2	moderate	$-5 \cdot 10^{-5}$	0.1
China	P_CHN_SIS	2	moderate	$-2 \cdot 10^{-7}$	0.1
	P_CHN_Northeast	3	moderate	0	0.2
	P_CHN_HSA	3	moderate	0	0.3
	P_CHN_YG	3	moderate	0	0.1
Australia	P_AUS_QLD	2	slow	$-2 \cdot 10^{-3}$	0.1
	P_AUS_NSW	2	slow	$-2 \cdot 10^{-3}$	0.1
Mongolia	P_MNG	1	high	$1 \cdot 10^{-2}$	0.6
Mozambique	P_MOZ	1	high	$1 \cdot 10^{-2}$	0.8

Appendix D: Results of COALMOD-World

Domestic trade flows

Table 8: Results of COALMOD-World: Domestic trade flows in Mtpa for all model periods

From	**To**	**2006**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
P_USA_PRB	C_USA_Rocky	94	63	52	44	39	34	30	28
P_USA_PRB	C_USA_Central	354	357	365	364	366	353	339	335
P_USA_PRB	C_USA_South					8	30	47	53
P_USA_PRB	C_USA_Gulf		70	70	70	70	70	70	70
P_USA_Rocky	C_USA_Rocky	16	40	50	56	60	60	60	60
P_USA_ILL	C_USA_South	70	70	70	70	70	70	70	66
P_USA_ILL	C_USA_Gulf	43	43	43	43	43	43	43	47
P_USA_APP	C_USA_South	34	35	37	37	32	15	1	
P_USA_APP	C_USA_East	56	57	58	58	58	57	56	55
P_USA_APP	C_USA_Gulf	133	115	118	117	117	113	109	101
P_POL	C_POL	65	67	67	64	60	54	49	37
P_UKR	C_UKR	30	32	34	34	34	34	33	31
P_KAZ	C_KAZ	40	43	45	45	45	45	44	44
P_RUS	C_RUS_Siberia	70	74	74	74	74	67	67	66
P_RUS	C_RUS_Central	16	21	23	20	18	13	13	13
P_ZAF	C_ZAF	88	96	107	110	109	101	89	75
P_IND_North	C_IND_East	82	102	83	77	104	135	170	170
P_IND_North	C_IND_North	139	150	169	192	230	273	321	321
P_IND_Orissa	C_IND_East	36	21	71	100	100	100	100	100
P_IND_Orissa	C_IND_South	41	56	6					
P_IND_West	C_IND_West	60	60	60	60	70	96	96	96
P_IND_South	C_IND_South	40	40	40	40	40	54	54	54
P_VNM	C_VNM	2	2	1					
P_IDN	C_IDN	20	24	25	24	23	23	23	23
P_CHN_SIS	C_CHN_Northeast			10	10	10	10	10	7
P_CHN_SIS	C_CHN_Main	328	415	450	450	450	450	462	462
P_CHN_SIS	C_CHN_Eastern	117	121	185	224	250	349	340	349
P_CHN_SIS	C_CHN_South	42		17	36				
P_CHN_SIS	C_CHN_SIS	219	276	320	347	347	347	345	339
P_CHN_Northeast	C_CHN_Northeast	148	188	209	218	238	238	238	238
P_CHN_HSA	C_CHN_Main			49	84	93	74		
P_CHN_HSA	C_CHN_Eastern	100	154	154	154	152	1		
P_CHN_YG	C_CHN_South	161	254	307	307	307	307	307	307
P_MNG	C_MNG	0.15	0.04	0.10	0.15	0.20	0.21	0.21	0.21

International trade flows

Table 9: Results of COALMOD-World: International trade flows in Mtpa for all model periods (part 1/2)

From	**To**	**2006**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
P_USA_PRB	C_JPN						5	5	5
P_USA_APP	C_CAN	15	15	16	15	15	14	14	13
P_USA_APP	C_MAR						1	4	
P_USA_APP	C_PRT						3	3	
P_USA_APP	C_ESP						11	9	
P_USA_APP	C_GBR					6	12	3	
P_USA_APP	C_DEU						2		
P_USA_APP	C_ITA						12	10	2
P_USA_APP	C_TUR						13	11	9
P_USA_APP	C_ISR						19	25	33
P_USA_APP	C_IND_West							15	37
P_COL	C_USA_Gulf	30							
P_COL	C_MAR				6	6	5		4
P_COL	C_PRT				5	4			
P_COL	C_ESP			5	14	14			
P_COL	C_GBR	15	46	43	28	12			
P_COL	C_DEU	20	19	28	24	17			
P_COL	C_ITA					16			
P_COL	C_TUR					7			
P_COL	C_KOR						19	35	32
P_COL	C_JPN						52	41	40
P_VEN	C_ESP			10	2				
P_VEN	C_NFB	9	10						
P_VEN	C_ITA				8				
P_VEN	C_TUR					9			
P_VEN	C_ISR					1			
P_VEN	C_IND_West								6
P_VEN	C_JPN						10	10	4
P_POL	C_GBR	9		7	20	25	25	25	25
P_KAZ	C_RUS_Siberia			5	3	0	0	1	2
P_KAZ	C_RUS_Central	30	30	30	32	34	34	34	34
P_RUS	C_PRT								2
P_RUS	C_ESP								8
P_RUS	C_GBR							5	0
P_RUS	C_NFB	13	11	22	21	19	16	14	10
P_RUS	C_DEU	13	14	4	6	11	21	20	15
P_RUS	C_DNK	8	8	8	8	7	7	6	4
P_RUS	C_FIN	10	10	9	9	8	7	6	4
P_RUS	C_ITA								6
P_RUS	C_TUR	15	15	15	15				
P_RUS	C_ISR					15	15	15	15
P_RUS	C_CHN_Eastern							18	20
P_RUS	C_KOR	2	17				25	7	5
P_RUS	C_JPN	17		15	18	18			

Table 10: Results of COALMOD-World: International trade flows in Mtpa for all model periods (part 2/2)

From	**To**	**2006**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
P_ZAF	C_MAR	5	5	6					
P_ZAF	C_PRT	5	5	5					
P_ZAF	C_ESP	18	17	2					
P_ZAF	C_GBR	25	4						
P_ZAF	C_ITA	13	19	18	8				
P_ZAF	C_TUR	4	4	4	3				
P_ZAF	C_ISR	3	15	18	24	11			
P_ZAF	C_IND_West		18	27	40	50	50	56	52
P_ZAF	C_IND_South			22	42	71	73	97	125
P_ZAF	C_THA						7		
P_ZAF	C_MYS						17	9	
P_VNM	C_CHN_South	20	20	1					
P_IDN	C_ISR	11							
P_IDN	C_IND_West	15							
P_IDN	C_IND_South	11							
P_IDN	C_THA	6	8	9	10	10	1	9	10
P_IDN	C_MYS	12	15	18	20	21		9	22
P_IDN	C_CHN_South	29	53	89	119	169	199	181	168
P_IDN	C_TWN	57	61	18	6				
P_IDN	C_PHL	7	9	11	12				
P_CHN_SIS	C_KOR	60	41	64	62	58			
P_CHN_SIS	C_JPN			16	28	41			
P_AUS_QLD	C_IND_South		8						
P_AUS_QLD	C_JPN	57	41						
P_AUS_QLD	C_TWN		8	57	57	57	60	60	60
P_AUS_NSW	C_ITA	6							
P_AUS_NSW	C_IND_South			20	16				
P_AUS_NSW	C_CHN_Eastern						35	25	8
P_AUS_NSW	C_CHN_South					19	1	14	19
P_AUS_NSW	C_KOR		3				4		
P_AUS_NSW	C_JPN	42	56	64	46	23			
P_AUS_NSW	C_TWN			1	23	37	39	40	52
P_AUS_NSW	C_PHL					11	11	11	12
P_MNG	C_RUS_Siberia	2	2						
P_MNG	C_CHN_Main			6	20	20	20	20	20
P_MNG	C_CHN_SIS	0		5	5	5	5	5	5
P_MOZ	C_ESP		0.98						
P_MOZ	C_GBR	1.00	0.02						
P_MOZ	C_ITA			0.11					
P_MOZ	C_ISR			0.54	0.91	4			
P_MOZ	C_IND_West					0.08	0.08	1	
P_MOZ	C_IND_South			0.35	0.09	4	12	12	12
P_MOZ	C_THA						0.23		

Appendix E: Validation of Results

Table 11: Validation of COALMOD's base case results for 2006: Imports in Mt (Source: own work based on IEA, 2008a)

Region	**Actual imports in Mt**	**Base case imports in Mt**	**Difference in Mt**	**Error**
Japan	121	116	5	4%
Korea	60	61	1	2%
Taiwan	57	57	0	0%
China	33	29	4	13%
USA	31	30	1	4%
India	25	26	1	3%
Turkey	15	18	3	22%
Malaysia	13	6	7	54%
Thailand	11	12	1	8%
Europe	178	163	15	8%
Average error				12%

Table 12: Validation of COALMOD's base case results for 2006: Exports in Mt (Source: own work based on IEA, 2008a)

Region	**Actual exports in Mt**	**Base case exports in Mt**	**Difference in Mt**	**Error**
Indonesia	147	150	3	2%
Australia	111	105	6	5%
Russia	81	77	4	5%
Colombia	62	65	3	5%
South Africa	72	72	0	0%
China	59	60	1	2%
Vietnam	23	20	3	13%
USA	20	15	5	25%
Kazakhstan	26	30	4	15%
Poland	13	9	4	31%
Average error				10%