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The end of cheap coal? A techno-economic analysis until 2030 using the COALMOD-World model

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HIGHLIGHTS

- COALMOD-World computes future domestic and global steam coal trade flows till 2030.
- Demand from India and China will drive an increase of the global seaborne trade.
- The global trade flows will shift towards Asia.
- The end of cheap coal will not be caused by geological reserve constraints.
- Infrastructure constraints will affect supply costs unless demand is stabilized.

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ABSTRACT

Questions about the future availability of inexpensive coal supplies are rising. In this paper a numerical model is developed to investigate the evolution of the international market for steam coal used for electricity generation. The "COALMOD-World" model is an equilibrium model that computes future trade flows, infrastructure investments and prices until 2030. The model includes the major domestic markets together with the globalized seaborne market and incorporates geological, technical and economical data and mechanisms. Two scenarios are explored: one with a continuously increasing global demand and another where the demand stabilizes after 2015. Rising demand in India and China will drive an increase of the international seaborne trade as well as a shift of global trade flows toward Asia. In the case of increasing global demand an end of cheap coal will not be caused by geological reserve constraints but rather by infrastructure constraints. Stabilizing future coal demand would be beneficial to both the climate and the global energy supply costs by keeping coal relatively cheap.

1. Introduction

This paper introduces a tool to analyze the future developments of the international steam coal market, the "COALMOD-World" model. The model includes virtually all producing and consuming regions in the world by modeling domestic markets along with the globalized seaborne market to see their interaction. 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's production capacity and transport infrastructure. Trade flows and investments may be subject to various capacity or expansion constraints. We assume profit maximizing players who optimize their expected and discounted profit over the total model horizon. In the model we integrate a wide range of geological, technical and economical data and mechanisms that aim at a more realistic depiction of the future coal market than is realized in previous models. We include the main drivers of the market such as future demand. Geological data is integrated in the form of reserves, heterogeneous coal qualities and with an endogenous costs mechanism that depends on cumulative production and investments. Technical constraints also influence the model outcomes and the whole model framework is grounded in economic theory and game-theoretic concepts.

We apply the model to two scenarios: one that sees global demand of coal continuously increasing and another where the demand stabilizes after 2015. As in both cases demand increases in Asia, especially in India and China, one main result of our modeling exercise is an increase of the international seaborne trade both in absolute terms and in relatives terms compared to global consumption. We also expect an increase in imports from Asia as well as a shift of global trade flows toward that region. Another

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significant result is that until 2030, the end of cheap coal will not be caused by geological reserve constraints but rather by infrastructure constraints. Especially in the scenario of a continuously increasing global coal demand driven by Asia and China, the market may not be able to supply enough steam coal due to restrictions in the expansion of mining and transport capacities. These restrictions affect not just domestic supply in India and China but also the global seaborne suppliers such as South Africa. Stabilizing world coal demand after 2015 will lead to a less tight future market situation. A stabilization of future coal demand will be beneficial both to the climate and to the global energy supply costs by keeping coal relatively cheap.

Our research is motivated by the fact that international trade and global demand for steam coal is mainly driven by demand in Asia. Thus we want to be able to identify how the interplay between domestic supply, exports and imports driven by demand as well as by supply costs and constraints will influence future trade flows and prices. Another area where we hope to make a contribution is to the discussion about "the end of cheap coal" outlined in the eponymous comment written by Heinberg and Fridley [19] in *Nature*. The authors argue that "useful coal may be less abundant than has been assumed" (p. 367). The authors cite three recent studies that predict a more or less imminent end of cheap and available coal through decreasing global production levels and rapid reserve depletion [39,20,37]. These studies are based on the concept of the Hubbert curve first described by M. King Hubbert [22]. The core mathematical assumption of this model is that cumulative resource production follows a logistic growth path that derived with respect to time yields the well-known symmetrical bell shaped curve of yearly production output; the summit of the curve representing the "peak" of the yearly production rate. Thus it is mathematically possible to estimate the shape of the curve and thus the peak year as well as the ultimately recoverable reserves, defined as the surface under the curve, based solely on historical production data.[1] This simple technique is subject to controversy. Its proponents claim that "the Hubbert curves are based on [...] production and not on ill-defined and subjective [...] 'reserves' " and that "historical production trends reflect the prevailing economics prior to the time of production" [39, p. 3111]. However its opponents, such as Lynch [33], state that the "work of the Hubbert modelers has proven to be incorrect in theory, and based heavily on assumptions that the available evidence shows to be wrong. They have repeatedly misinterpreted political and economic effects as reflecting geological constraints, and misunderstood the causality underlying exploration, discovery and production"(p. 30). We do not intend to settle the general debate about the Hubbert curves but rather make a critical evaluation of the three aforementioned papers using this method for coal. We give an overview of the papers starting with the earliest predicted "peak coal", finishing with the one with the latest peak date.

Patzek and Croft [39] predict the global coal peak as early as 2011. The methodology used is the closest to the one described by Hubbert. The authors use historical production data to fit Hubbert curves for each coalfield and then sum the data up. Hence the name "multi-Hubbert cycle analysis". To be able to perform this summation, the authors assume that coal mines are "independent of each other" in terms of production. We find this to be a rather strong assumption. For example a power plant located in Southern China that is able to choose between domestic coal from northern Shanxi or imported coal from Indonesia will make an economic calculation based on the extraction and transport costs. Thus if coal from Indonesia is cheaper to source, the higher production from Indonesia will cause lower production in Shanxi, ergo the mines are not independent. Also there may be some problems with using only historical production data. The imminence of the predicted peak in China, also 2011, may be due to the fact that infrastructure constraints, reforms and price regulations that can slow down production are interpreted as geological depletion. Indeed Peng [41] found that the effect of the recent coal market deregulation, while power prices are kept regulated, is that "under pressure of price increases from domestic coal suppliers the power sector responded by going to overseas markets to purchase coal". Interestingly, another study by Lin and Liu [29], also using the Hubbert curve methodology, predict a much later time for the peak, between the late 2020s and the early 2030s. Patzek and Croft [39] also concede that "Hubbert cycle predictions almost always underpredict the true future production rate of a resource" but argue only verbally why new production capacity will be hard to put in place due to transport or environmental restrictions. This is essentially a question of investment dynamic that the Hubbert curve model is not able to integrate. Also, past production can only represent past economic situations. The simple Hubbert model fails to integrate paradigm shift that will affect the future production pattern such as the carbon constraints of climate policy or the high economic growth in Asia.

Höök et al. [20] use a more refined model as they integrate past production and reserve estimates for the Hubbert curve fitting. In the "standard case outlook" the authors predict the peak around 2025–2030. The global production level at that time is in the same range as other projections such as the IEA [26] World Energy Outlook Current Policies scenario. The authors discuss reserves estimates extensively and show how they developed over time. The underlying reserve estimations of the "standard case outlook" is more restrictive than the ones of national geological services such as the USGS or the German BGR and does not account for the expansion of the reserves. Thus the authors also model a "high case outlook" with a doubled reserve base. Logically the peak is further in the future, around 2040. But the estimated annual production values also increase and after 2015 these values are significantly higher that the estimates of the IEA [26] World Energy Outlook Current Policies scenario that represents the worst case in climate policy. The Hubbert method, by trying to fit a bell curve, overestimates future production. This is caused by the fact that realistic demand projections are not included in the model by Höök et al. [20]. The higher reserves of the "high case outlook" would then mean that significant amounts of coal are available for at least 100 years.

The most complex model is developed by Mohr and Evans [37]. They include supply and demand reactions, some form of investment (mine upgrade) mechanism and distance themselves from the classic Hubbert methodology because "there is no underlying theory explaining why production ought to follow a symmetric bell curve". Using their model the authors predict a peak in 2034 in the "Best Guess scenario" and are able to produce an extraction path with a plateau with realistic maximal yearly extraction rates. However the model also relies on the fitting of historical data, that comes with the issues discussed above, and needs input values for constants that seem difficult to estimate. The supply and demand interaction, as well as the mine upgrades, is not based on economic theory but on a mathematical mechanism using "supply gap" values. The authors also recognize that the iterative process used to compute the equilibria in the model takes "several hours to run" and that "the number of constants makes application of the model difficult and time consuming".

In our paper we would like to change the affirmation made by Heinberg and Fridley [19] about "the end of cheap coal" into a question and show that equilibrium modeling may be the better way to answer that question because it is able to integrate market and investment mechanisms as well geological and infrastructure constraints.

[1] A description of the mathematical transformations is given in Claerbout and Muir [7].

2. Equilibrium modeling of energy resource markets

An extensive review of the – rather sparse – coal-market specific modeling literature is provided in Haftendorn and Holz [16]. Altogether, there is little modeling effort applied to international coal markets in general and in particular using modern modeling techniques provided by equilibrium modeling. Kolstad and Abbey [27] are a notable exception, but their static analysis covers the 1980s. However, both the situation on the international steam coal market as well as modeling techniques have since evolved. Paulus and Trüby [40] use a spatial equilibrium model to show how a Chinese infrastructure decision, transporting coal-based electricity over long distances to the demand centers rather than the coal itself, could affect the global market positively through reduced Chinese imports.

We follow 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" [16], as well as in the multi-period modeling experience of other markets (e.g., [9,10,24]). 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., [8]). 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. These are formulated 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 is wide interest in modeling natural gas markets, both at the European and the global levels. Huntington [23] provides an overview of some of these models. Similar to the path that coal market modeling is 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, one must use modeling techniques that can represent strategic players, such as equilibrium modeling. Equilibrium modeling of natural gas markets, first with static models, was initiated by Mathiesen et al. [34] and especially Boots et al. [4]. Once this model technique was well developed in the static context, attention turned to the inclusion of investment decisions in a multi-period framework [30,10]. 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 changing short-term production cost curves. Lise and Hobbs [30] 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 at representing 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. [10] 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 [18], 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 on 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 [25] and needs better modeling. The FRISBEE model [1] is a model of the global oil market with a focus on the Organization of Oil Exporting Countries (OPEC) and its production economics. The Oilmod model [24] 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 limited in the near future for some countries [5].

3. The model

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 as well as 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 exclusively used by one company or used by multiple companies, with a variety of possible ownership structures. *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 [16], we provide an analysis of the market structure for 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 Fig. 1. The two model player types, producers and exporters, will maximize their profit in a perfectly competitive way and thus act as price takers.

In Fig. 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 this capacity is 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

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

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

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

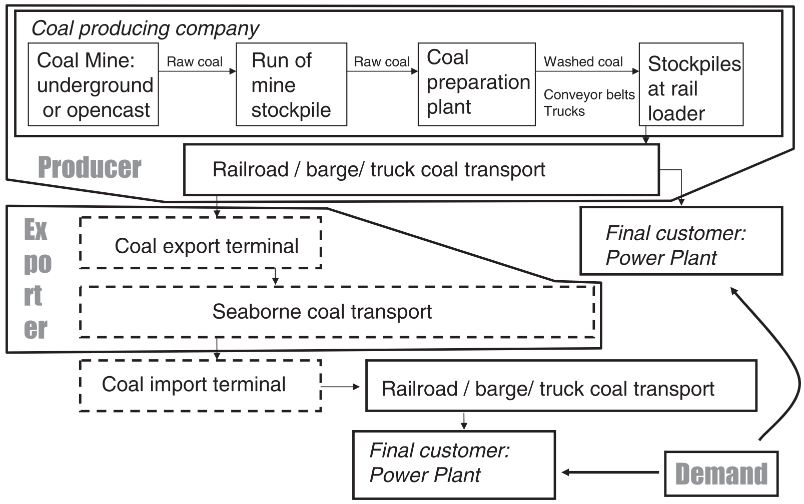


Fig. 1. Model players on the steam coal value-added chain.

for the sea transport. These players are aggregated at a national or regional (sub-national) level.

Research on international coal markets points out that the traditional separation of the Pacific and the Atlantic market has faded (e.g., [11,46,28,47]). In our model, we therefore consider the global market as one integrated market, albeit the spatial aspect of the market where transport costs play a role in determining the trade relations is not neglected.

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. 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.

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.

Fig. 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 not only calculates an equilibrium within each model year but also over the total model horizon regarding optimal investments. For the years between the model years we interpolate the produced quantities since these are necessary in order 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 producer and exporter 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.

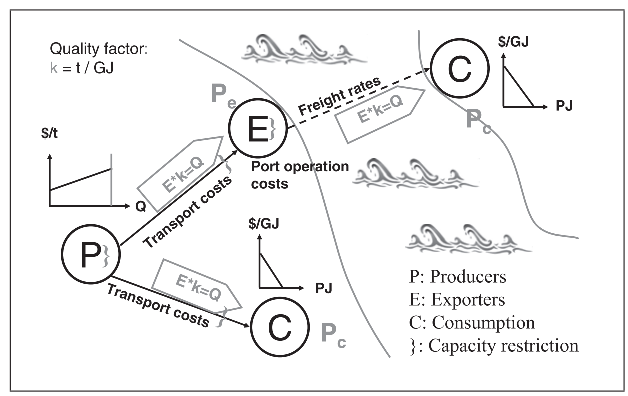


Fig. 2. COALMOD-World model structure.

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

- *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

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

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.

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

s.t.

$$Pcap_f - \sum_{a'<a}\left[\left(\sum_c x_{a'fc}\cdot\kappa_{a'f} + \sum_e y_{a'fe}\cdot\kappa_{a'f}\right)\cdot mc\_int\_var_f\right] + \sum_{a'<a} Pinv_{a'f} - \left(\sum_c x_{afc}\cdot\kappa_{af} + \sum_e y_{afe}\cdot\kappa_{af}\right) \geqslant 0 \quad \left(\alpha_{af}^P\right) \quad (2)$$

$$Pmaxinv_{af} - Pinv_{af} \geqslant 0 \quad \left(\alpha_{af}^{Pinv}\right) \quad (3)$$

$$Res_f - \sum_{a\in A}\left[\left(\sum_c x_{afc}\cdot\kappa_{af} + \sum_e y_{afe}\cdot\kappa_{af} + \sum_c x_{a-1fc}\cdot\kappa_{a-1f} + \sum_e y_{a-1fe}\cdot\kappa_{a-1f}\right) * \frac{5}{2}\right] \geqslant 0 \quad \left(\alpha_f^{Res}\right) (4)$$

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

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

$$Tmaxinv\_c_{afc} - Tinv\_c_{afc} \geqslant 0 \quad \left(\alpha_{afc}^{Tinv\_c}\right) \quad (7)$$

$$Tmaxinv\_e_{afe} - Tinv\_e_{afe} \geqslant 0 \quad \left(\alpha_{afe}^{Tinv\_e}\right) \quad (8)$$

$$x_{afc} \geqslant 0; \quad y_{afe} \geqslant 0; \quad Pinv_{af} \geqslant 0; \quad Tinv\_c_{afc} \geqslant 0; \quad Tinv\_e_{afe} \geqslant 0 \quad (9)$$

In the second line of the producers' objective function (1), we see that 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. 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) that must hold over the total model horizon. Eq. (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. Eq. (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.

- *The production cost function*

In this section, we specify the production cost functions for each period that were left undefined in Section 3.2. 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:

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

This leads to the following linear marginal cost function:

$$mc_f = mc\_int_f + mc\_slp_f\cdot q_f \quad (11)$$

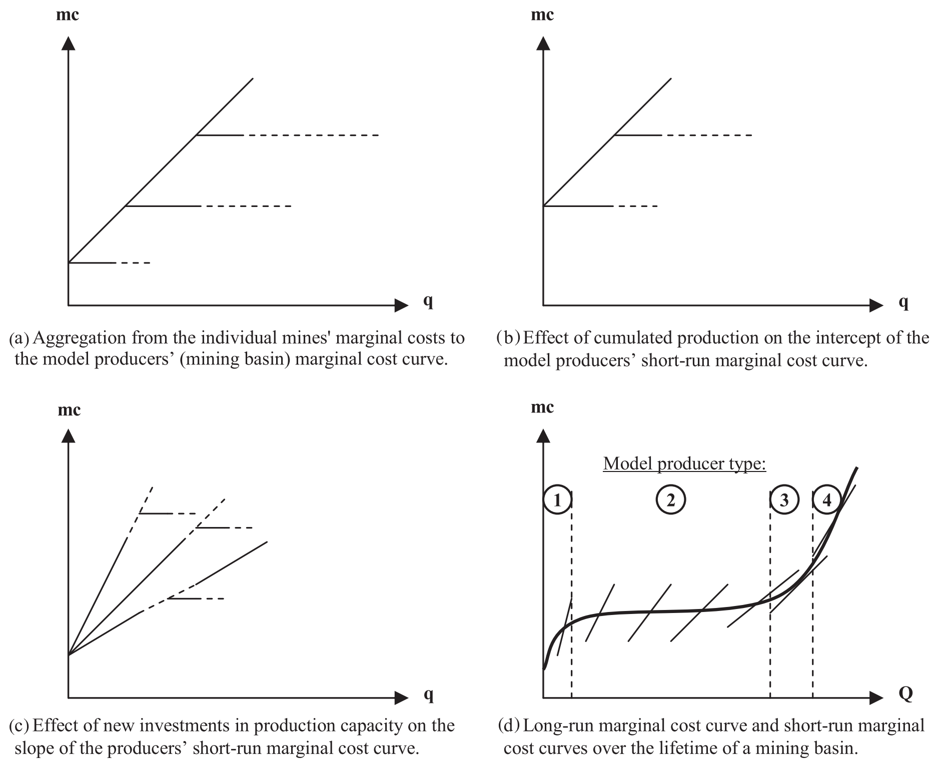
Since we have an energy based model but mass dependent production costs, we use the conversion factor κ_f explained in detail in Section 3.4 to obtain the following marginal cost function depending on the quantity q_f expressed in energy units:

$$\kappa_f\cdot mc_f = \kappa_f\cdot mc\_int_f + \kappa_f^2\cdot mc\_slp_f\cdot q_f \quad (12)$$

Some resource markets models use the same short-run costs for every model period (e.g., [10]). This is not a realistic solution for a model of the coal market since there are many potential factors influencing future costs and changing short run costs. Other models only use the long run marginal costs (e.g., [31]). 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 [16], 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 [3]. 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 [43] 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.

At the highest level of aggregation Rogner [43] 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 Fig. 3d. We assume that a mining basin, because it also represents a high level of aggregation, has a similar cost development as the cumulative 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 Fig. 3d. First, a mining basin has some easily 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 completely mined, costs start to increase more or less proportionally with the cumulative production. Fourth, and finally, for the last deposits that are hard to reach, extraction costs rise rapidly. Each coal mining basin can be put in relation with



(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.

Fig. 3. Endogenous cost mechanism in relation with short and long-run marginal costs.

one of these four types. Consequently, we assign each producer to one such type.[6] This determines how the short-run costs will develop between 2010 and 2030. Before we categorize the producers, we explain the endogenous cost mechanism starting at the individual mine level.

Fig. 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 in 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 it with its 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 cumulative production, as illustrated in Fig. 3b. We follow the rules stated by Hotelling [21] that for exhaustible resources, the cheapest deposits are extracted first and go further by assuming that, even if all the mines along the cost curve may produce coal in one period, the cheapest mines are depleted first.[7] The principal reason is that, generally, the cheap mines are the oldest ones in operation. The effect of cumulative production from one model period to another makes the cheapest producer in Fig. 3a disappear from the cost curve. This causes the intercept of the cost function to increase as shown in Fig. 3b. This is the core of the first endogenous cost mechanism that enters the model with the following equation:

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

Eq. (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 determines the position on the cost curve of the previous period to determine the new intercept. Graphically, this is the passage from Fig. 3a to Fig. 3b. If the factor is one it means that the cumulative production leads to a complete depletion of all the mine capacity that produced in the last period. 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 to the *slope* of the marginal cost curve. Graphically, this is represented by the step that leads from Fig. 3a to Fig. 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 Eq. (14), represents the effect of the cumulative investments in production capacity on the slope of the marginal cost curve. A value of zero is used in the case that there is no influence of the investments on the slope (model

[6] In the current model setup until 2030 each model producer stays in the assigned type. However, for longer-term simulations a dynamic setup where producers change types could also be implemented.

[7] This may not always be true in reality as some old and cheap mines may still have decades of life expectancy. We do not model individual mines but provide a reasonable approximation for the developements on a mining basin basis. The existence of cheap mines that will operate for a long time can be captured in our endogenous cost mechanism by a slow increase in the intercept and a decrease in the slope of the marginal cost curve. This is for example the case in the Powder River Basin.

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 types 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.[8]

- *Mine mortality mechanism*

The logic behind the mine mortality mechanism is already included in the previous chapter about endogenous costs where we explained that the factor $mc\_int\_var_f$ determines how fast the cheapest mine are mined out and thus also the mine mortality, or how much of the existing capacity disappears relative to the cumulative production over the years. The term that is subtracted every year and is included in the production capacity restriction in Eq. (2) of the optimization problem and Eq. (29) of the KKT conditions is $-\sum_{a'<a}\left[\left(\sum_c x_{afc}\cdot\kappa_{af}+\sum_e y_{afe}\cdot\kappa_{af}\right)\cdot mc\_int\_var_f\right]$.

3.3. The exporters' problem

The exporters maximize their profit, $\Pi_e^E(z_{aec}; Einv_{ae})$. Each exporter is linked to a maximum of one producer. 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 $Einv_{ae}$.

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

s.t.

$$Ecap_e+\sum_{a'<a}Einv_{a'e}-\sum_c z_{aec}\cdot\kappa_{ae}\geqslant 0 \quad (\mu_{ae}^E) \quad (16)$$

$$Emaxinv_{ae}-Einv_{ae}\geqslant 0 \quad (\mu_{ae}^{Einv}) \quad (17)$$

$$Emaxcap_e-Ecap_e-\sum\nolimits_a Einv_{ae}\geqslant 0 \quad (\mu_e^{Emax}) \quad (18)$$

$$z_{ec}\geqslant 0; Einv_{ae}\geqslant 0 \quad (19)$$

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. Eq. (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 during which model year the port expansions should take place. The symbols in parentheses are the dual variables associated with the constraint.

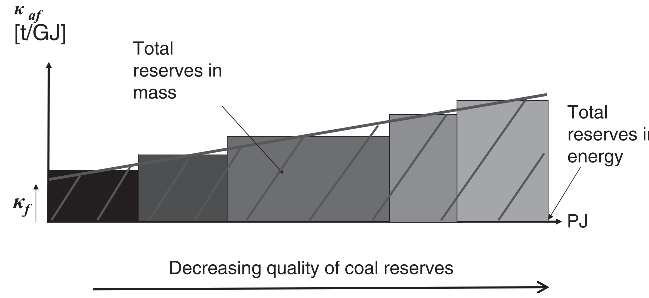


Fig. 4. Producer's quality definition relative to its reserves.

3.4. Other model equations

- *Quality equation*

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. Fig. 4 visualizes this fact and shows how it would affects the model.[9] 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. Eq. (20) formulates this relationship between reserves and coal quality mathematically.

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

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.

- *Final demand*

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

$$p_{ac}-p_{ac}\left(\sum\nolimits_f x_{afc},\sum\nolimits_e z_{aec}\right)=0, \quad p_{ac}\ (\text{free}) \quad (21)$$

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 $\left(p_{ac}^{ref}\right)$ and reference demand value (q_{ac}) for the model starting year 2006 and use projections for future years. We make assumptions about 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 $q_{ac}=\sum_f x_{afc}+\sum_e z_{aec}$:

[8] The only detail that must 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 Eq. (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.

[9] This feature is integrated in the model but has not been used for the simulation runs of this paper due to the lack of data to properly determine the parameter δ_f. Thus this parameter is set to zero for all producers in Eq. (20).

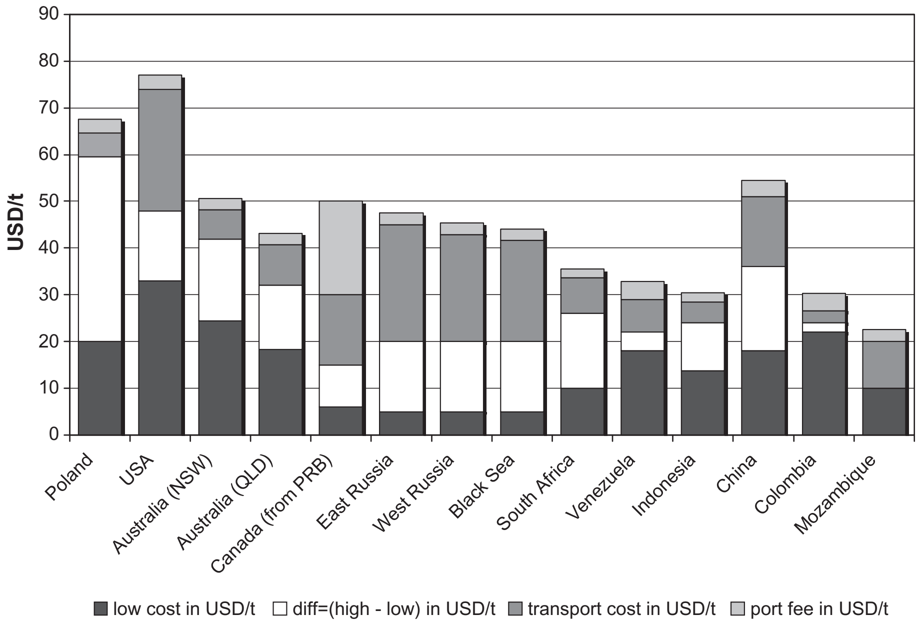


Fig. 5. FOB costs for all export countries implemented into COALMOD-World. *Source*: own work based on [2,42,38].

Table 1
Reserves of major countries in COALMOD-World in Million tons. *Source*: own work based on [12,15,38].

China	270,800	Australia	38,593
US	270,718	Poland	13,997
Eurasia	93,494	Indonesia	10,000
India	63,968	Colombia	6229
South Africa	48,740	Mongolia	1170

Table 2
World Energy Outlook demand projections for coal for power generation in the Current Policies and New Policies scenarios converted to Petajoules. *Source*: own work based on [26].

Region	Current policies				New policies	
	2006	2015	2020	2030	2020	2030
WORLD	86,876	110,155	119,031	140,216	106,931	107,810
OECD N.A.	22,064	22,776	22,106	21,897	21,101	18,129
US	20,808	21,227	20,892	20,683	20,139	17,459
OECD Pacific	6406	6783	6866	6364	6029	4271
Japan	2554	2680	2470	2219	2219	1424
OECD Europe	10,132	9127	8876	8081	6866	5359
EU	10,312	9043	8415	7243	6490	4815
Eurasia	6322	6322	6071	6908	5568	5485
Russia	3433	3768	3475	4271	3224	3224
Non OECD Asia	38,812	61,127	70,673	91,356	63,556	70,673
India	7249	9043	11,807	16,287	10,844	12,812
China	28,973	47,143	52,419	64,937	47,018	50,242
Middle East	335	419	544	879	419	586
Africa	2512	2847	3182	3894	2721	2680

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

- *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.

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

Appendix A shows the KKT (Karush–Kuhn–Tucker) optimality conditions of each model player that together with 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 [14].

4. Model specification and data

4.1. Countries and nodes definition

We include all countries that were either consuming at least 5 Mtpa[10] or producing and exporting at least 5 Mtpa in 2006. Some additional countries that are expected to become relevant players in the global market between 2010 and 2030 are included as well (e.g., Mongolia, Mozambique).

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 US, China, India and Australia. The complete list of the countries and nodes in the model can be found in Table 3 in Appendix B.

4.2. Data

The data collection required a major effort since there is no central source available. We collected data from publicly available sources.[11] A detailed overview of all the data and data sources can be found in Haftendorn et al. [17].

[10] Mtpa: million tons per annum.

[11] 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.

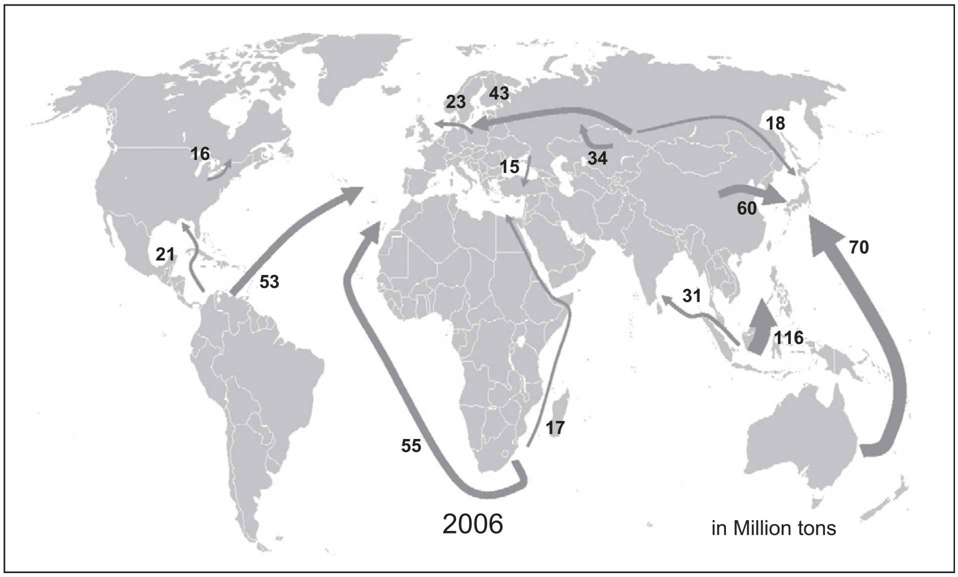


Fig. 6. Increasing demand scenario results 2006: seaborne trade flows (in Mt).

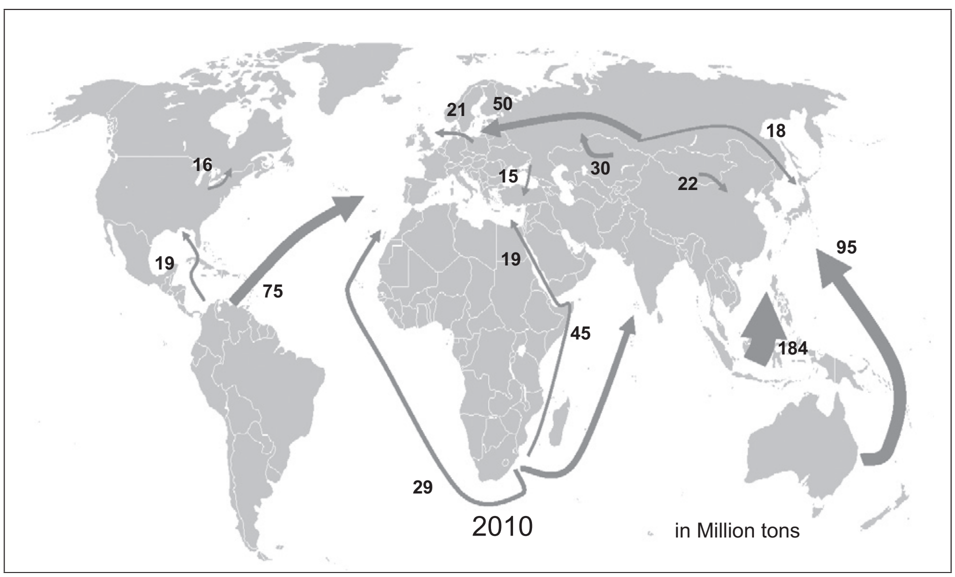


Fig. 7. Increasing demand scenario results 2010: seaborne trade flows (in Mt).

Fig. 5 shows the FOB costs for each exporter. In sum the cost of a ton of exported coal adds up from production costs, land transport costs and the export fee. In this figure, we also include the range of production costs in the respective production area. The dark part labeled low cost represent the cost of producing the first ton of coal and the dark and white part together represent the production costs at production capacity.

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 4 in Appendix C 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 information about the 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 [36], EPRI [13] and Ritschel and Schiffer [42]. For the US the report by Luppens et al. [32] that is part of the National Coal Resource Assessment Overview is used.

We assume that there are restrictions on production and export capacity expansions for various reasons that can be geological, technical and economical (financial restrictions, lack of qualified labor force or equipment). These restrictions are based on historical capacity data provided by the USGS in the country reports of the Mineral Yearbook[12] on historical production and export capacity data as well as export capacity expansion plans. The data for these restrictions can be found in Table 5 in Appendix C.

In Table 1 we show the distribution of global steam coal reserves by major global producing regions used in the model. In order to use consistent reserves data, we base ourselves primarily on one source: Energy Information Administration [12, Table 8.2]. This data is aggregated at a national level, thus to get the distribution on a sub-national level other sources had to be used. For the US,

[12] http://minerals.usgs.gov/minerals/pubs/country/.

Energy Information Administration [12, Table 15] is used. The reserve distribution to the Indian production nodes is based on the Geological Survey of India [15] and for the Chinese producers on the National Bureau of Statistics of China [38]. For Indonesia we considered the reserve number of 4967 Mt too restrictive given the relatively low exploration activity in large portions of Kalimantan, which are thought to be coal rich. Thus the estimate of 10,000 Mt, roughly the double of the present estimates.

The demand side of the model is based on the IEA's World Energy Outlook's demand projection [26] shown in Table 2. We implement the two main scenarios. In the increasing demand scenario, based on the IEA Current Policies scenario, it is assumed that as of mid-2010 no change in the current policies will be implemented and that the recently announced commitments are not acted upon. In the stabilizing demand scenario, based on the New Policies scenario, the recently announced commitments and policies, for example the ones of the 2009 Copenhagen Climate Conference, are fully implemented. However, the IEA data is aggregated, so the demand projections of the IEA [26] 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.

5. Results

5.1. General assumptions and base year results

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.

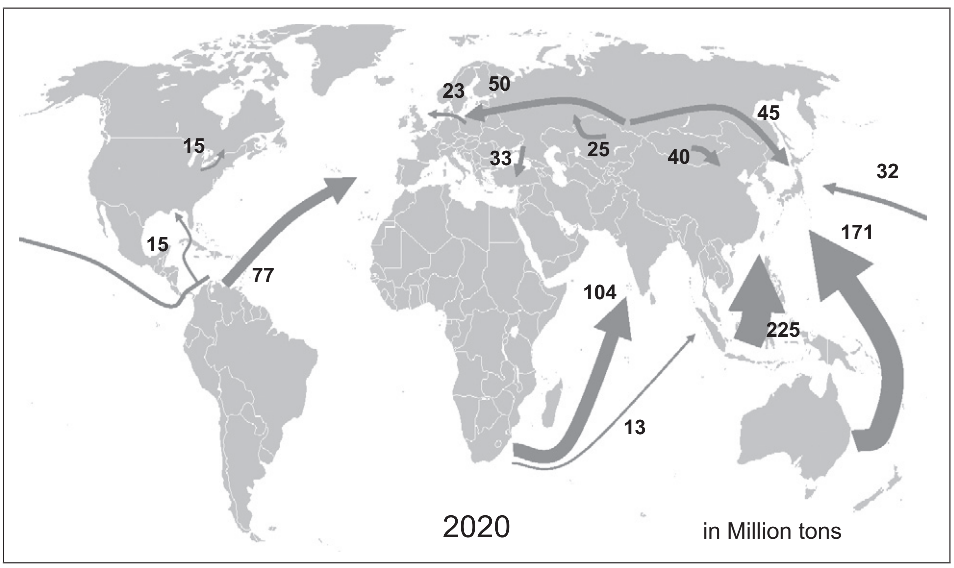


Fig. 8. Increasing demand scenario results 2020: seaborne trade flows (in Mt).

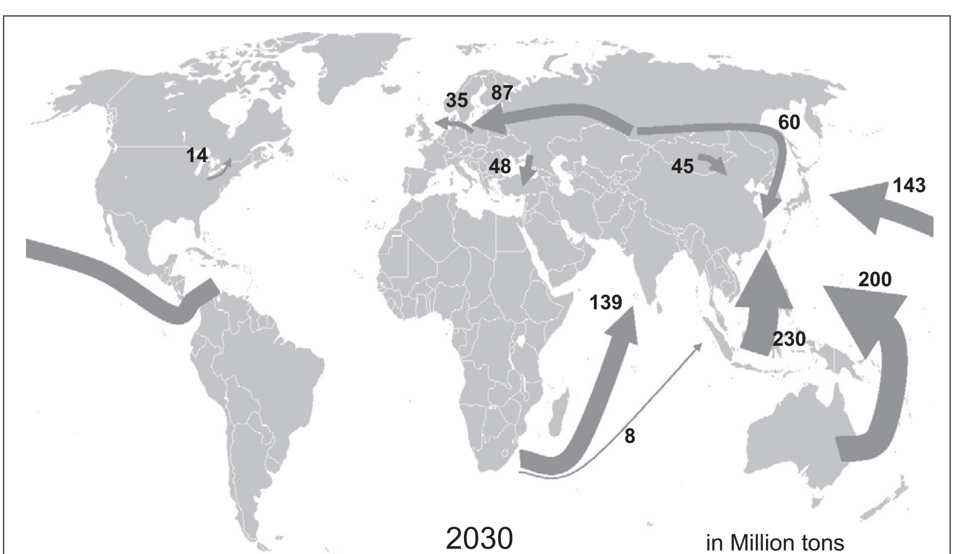


Fig. 9. Increasing demand scenario results 2030: seaborne trade flows (in Mt).

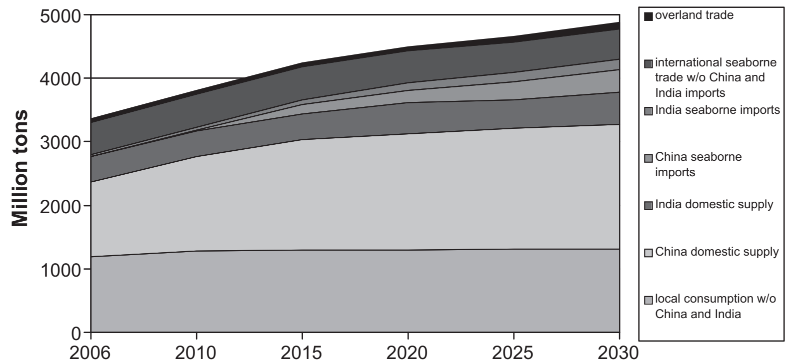


Fig. 10. Increasing demand scenario: aggregated consumption and imports (in Mt).

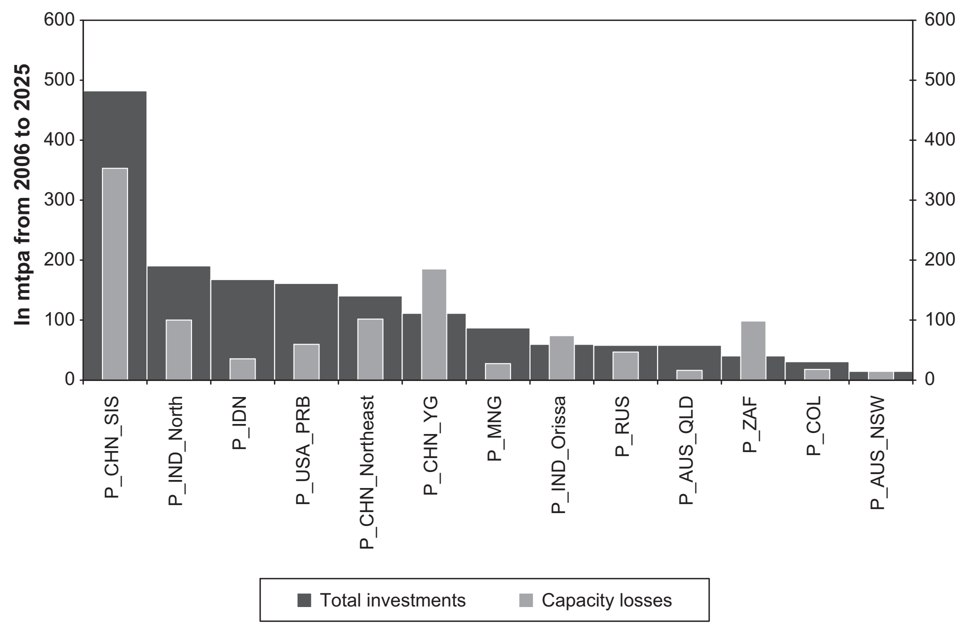


Fig. 11. Investments in additional mining capacity and capacity losses of producers between 2006 and 2025 (in Mtpa).

Our results are based on the assumption of competitive and liberalized markets.[13] 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 which countries investments should take place.

The results for 2006 show a good similarity with the actual observed trade pattern. The direction and relative amounts of the trade flows correspond to actual trade flows.[14] This is an important achievement given that we not only simulate the trade flows shown on the maps in Figs. 6–9 and 13 and 14 but also simulate internal markets.[15] For the purpose of model validation we also computed the Mean Absolute Percentage Errors for the level of exports and imports from every country. The values are 19.4% for the exports and 12.4% for the imports. Modeling the interaction between imports and domestic supply is a difficult task since for demand nodes with these two sourcing possibilities we assume total substitutablility. 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.[16]

5.2. Increasing demand scenario

Figs. 6–9 show the evolution of the global seaborne trade flows from 2006 to 2030 for the Increasing demand scenario.

Australia and Indonesia remain key players in the Pacific market. Their exports increase significantly and reach the high levels of 200 Mtpa for Australia in 2030 and 230 Mtpa for Indonesia. Indonesia has been the most dynamic player between 2000 and 2007, and now has greater exports than Australia. Our

[13] 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 toward competitiveness in the future.

[14] The only notable exception being the lower levels of exports from Australia to Japan. Here we suspect a strong bilateral relationship and long-term contracts to play a role. In the subsequent years when the markets get tighter the Australian exports return to normal levels at production capacity.

[15] COALMOD-World is an energy-based model that calculates trade flows in Petajoules. For better representation, the results shown in Figs. 6–9 and 13 and 14 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.

[16] An optimal modeling exercise would require a database at 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.

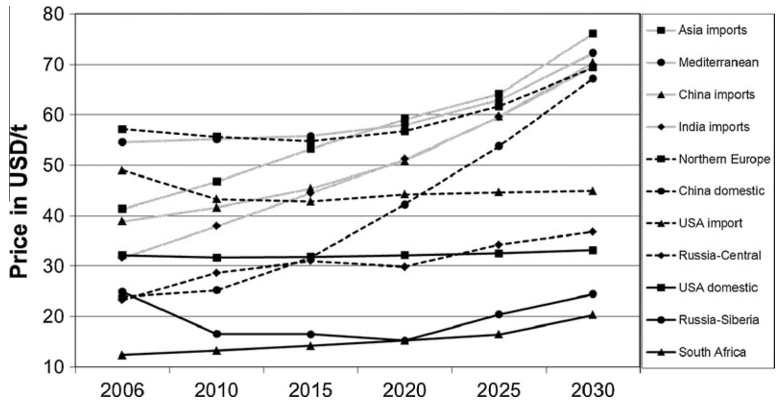


Fig. 12. Increasing demand scenario: computed average prices representing the marginal costs of supply of selected regions for all model years (in 2006 USD/t).

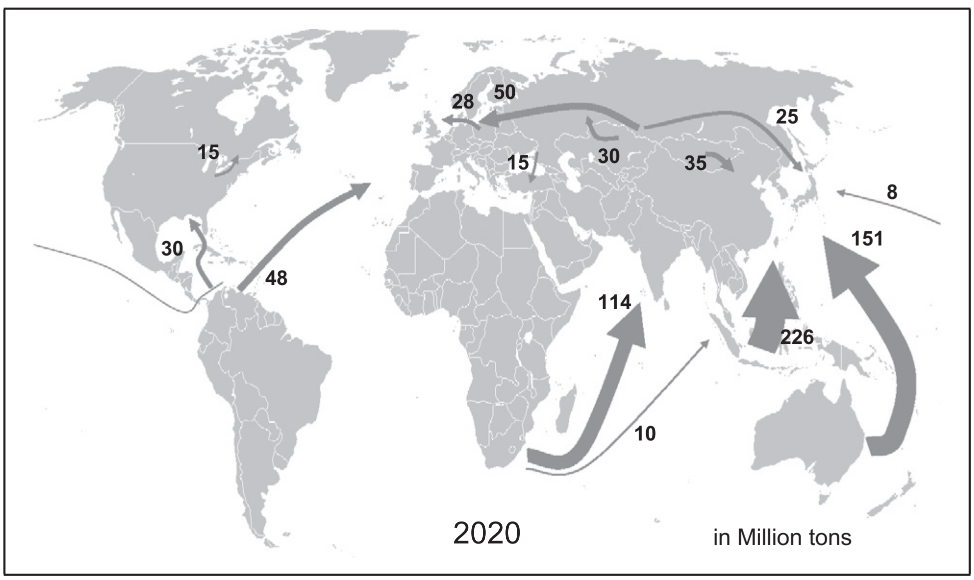


Fig. 13. Stabilizing demand scenario results 2020: seaborne trade flows (in Mt).

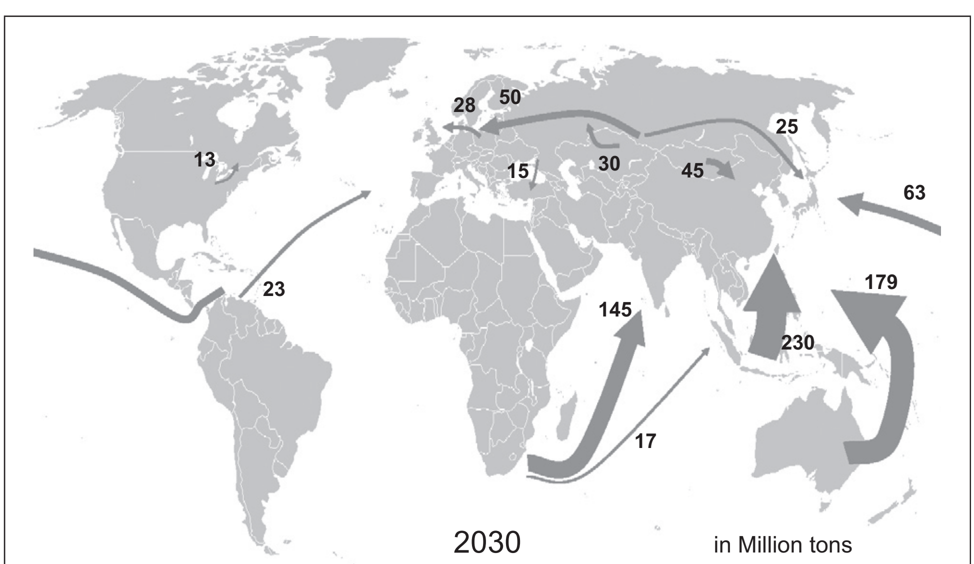


Fig. 14. Stabilizing demand scenario results 2030: seaborne trade flows (in Mt).

model confirms this trend for 2010 and forecasts that Indonesia consolidates its role as the leading steam coal exporter, ahead of Australia. Low production costs and flexible, low cost investments are the main reasons for this development.

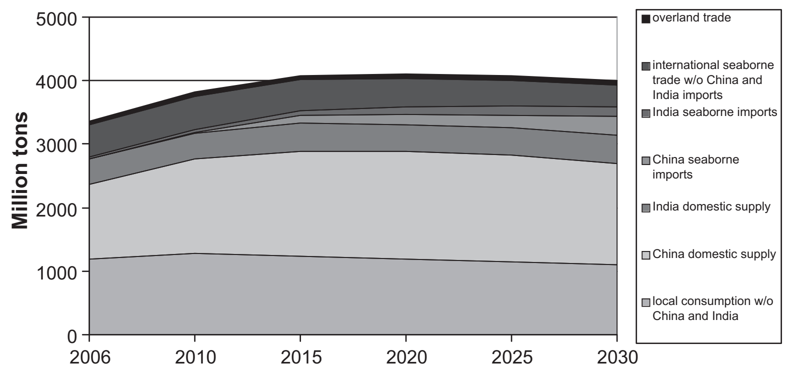


Fig. 15. Stabilizing demand scenario: aggregated consumption and imports (in Mt).

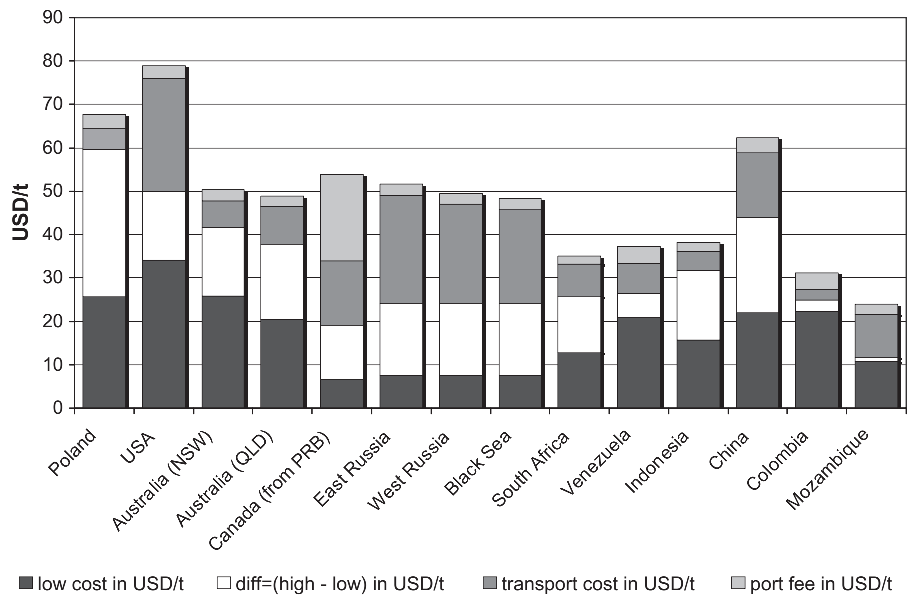


Fig. 16. 2020 FOB costs for all export countries calculated endogenously in the stabilizing demand scenario.

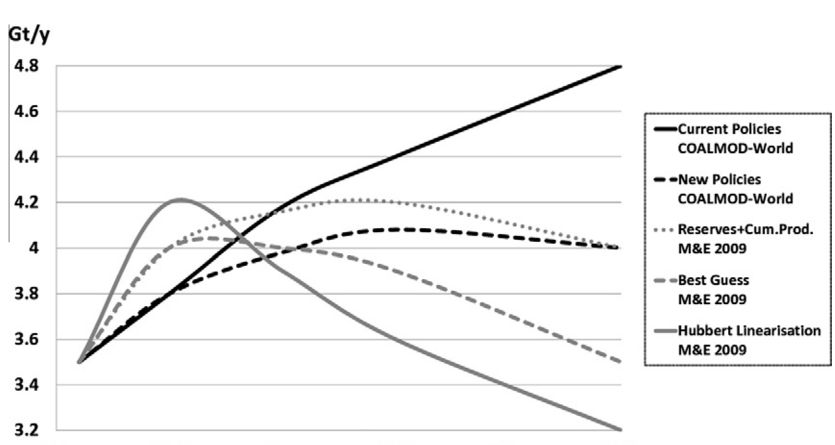


Fig. 17. Comparison of production projections in COALMOD-World and Mohr and Evans [37] for bituminous coal (in Gt per year).

The third most important exporter is South Africa with an export level that doubles between 2006 and 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 Ocean market and South Africa would become the key player in this market.

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 2020, Russia become the most important supplier to Europe in 2030, exporting nearly 95 Mt. The US play a relatively small role on the Atlantic market as an importer of Colombian coal from 2006 to 2020 and are self-sufficient in the remaining years.

Before 2015 China is a swing supplier on the world market with a high variability of exports. China becomes a net importer in 2010 and completely ceases to export after 2015 due to the high internal demand. China's exports amount to 60 Mt in 2006 and 26 Mt in 2015. 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.

From 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 where South Africa and Colombia are the main suppliers to the Atlantic market and Indonesia and Australia to the Atlantic Market. Then, we notice a gradual shift eastwards until 2020 with flows from South Africa being directed toward Asia and, especially, India. Colombia replaces South Africa as the key supplier to Europe. The second step in the shift starts in 2020. We expect an additional shift westwards with Colombia delivering to Japan and Korea, resource poor countries with a high willingness to pay.[17] By 2030, the overall picture on the global market has significantly changed: Russia and Poland are the only suppliers to Europe; South Africa, Europe's traditional supplier, is a major supplier to India and the Pacific market; and Colombia becomes, principally, a Pacific market supplier. Asian market demand is very strong, especially China, which is importing significant quantities from Russia and Mongolia, 60 and 45 Mt respectively. Fig. 10 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 36–48% of the worldwide consumption in every model year. The volume of the international seaborne trade increases by 86% from 2006 to 2030 and its share in total consumption increases from 16% to 21%. Also, China and India account for most of this trade increase as their seaborne imports are multiplied by 11.6 from 2006 to 2030. In 2030, the Chinese and Indian imports represent close to half of the international trade. Seaborne imports of other countries amount to 478 Mt in 2006 and increase to a level of 520 Mt in 2015 to then gradually return to the level of 2006 in 2030.

The model also gives us the amount of investments in mining, transport or export capacity necessary to serve the high demand predicted by the increasing scenario. The cumulative amount of investments in mining capacity from 2006 to 2025 for the main model producers in shown with the black bars in Fig. 11. This figure also shows the losses of mining capacity that resulted from the mine mortality mechanism described in Section 3.2 represented by the gray bars. Thus the difference between those two bars represents the net capacity addition (or loss) during the time between 2006 and 2025. The most important net capacity addition occur in Northern China, Northern India, Indonesia, the Powder River Basin in the US, and to a lesser extend in Mongolia and Queensland, Australia. The net capacity losses are due to the fact that in certain producing regions (more than represented in Fig. 11) the reserves are getting closer to exhaustion and extraction costs increase. In South Africa the loss of capacity is due to the fact that in the model the South African coal producer can deliver coal to both export and domestic market without any restriction or domestic obligation. This results in a diversion of local supplies to the export market penalizing and reducing the supplies to the domestic market (see Fig. 12 for the price effect). A domestic obligation or the dedication of production capacities to the domestic market could be implemented to remedy this but would not affect the export and global results of our model as the investments in production capacity would then be higher.

The increasing demand scenario represents the worst case for climate policy but also for the coal market and the coal consuming countries. This is due to the potential restrictions that may affect an expansion of the production and export capacities and that we have tried to implement in the model. A few example for the rationale of these restriction is provided in the next paragraph.

In the US, production 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.[18] The Chinese coal industry is in a process of a difficult restructuring. The small, dangerous and often illegal township and village enterprise (TVE) mines must be closed to make room for more efficient larger firms [35]. As of 2009 TVEs still accounted for 38% of national coal output [45] but after the state driven market restructuration is complete other factors could limit Chinese production expansion and increase the need for coal imports. Investments cost are growing and will continue to grow as larger firms require more upfront capital investments and there will be a move of the production towards less attractive deposits that are deeper or further away from the coastal demand centers [45,44]. In India the reform process from state run enterprises to efficient firms is even more cumbersome [6]. The increase in Indian production capacity might also be limited by political and technical factors.

In the model a restriction that is binding has a positive dual variable. In the increasing demand scenario we see a lot of binding restrictions and positive dual variable for the capacity constraints on production and exports but also on the expansion of those capacities. This is especially true for India and China where more restrictive limitations were imposed but also for the exporters that try to satisfy this growing demand such as Indonesia, Colombia, Australia or South Africa. The effect of these restrictions can be seen in the prices that are discussed in the next paragraph.

Fig. 12 shows the price development for some major regions. It is important to note that these prices represent marginal costs of supply computed by a model based on the assumption of perfect competition. Other factors that may affect the prices such as long-term contracts, short-term disruptions, local market power and other market distortions are not included here. Globally, the

[17] 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 facilitate Colombian exports to Asia.

[18] 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.

computed prices show an upward trend between 2006 and 2030. The lowest prices with the lowest increase over time are the domestic prices in South Africa, the US and Russia. These demand nodes are close to large and cheap sources of supply. They is some effect of the global market such as in South Africa, but it is limited. We can also see that for the Russia-Central and Russia Siberia domestic prices increase after 2020. This is due to the increased exports to Europe in these years. The highest rise in prices occur in the Indian and Chinese prices. The India import prices as well as the Chinese domestic and import prices all converge to the same level as that of European and other Asian importers. This is due to the high rise in imports but also domestically because the very high production makes it necessary to use more expensive reserves.

Table 3
Nodes of the COALMOD-World Model.

Country	Producers		Exporters		Consumers		Port
Canada					C_CAN	Ontario	No
US	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			

5.3. Stabilizing demand scenario

The results of the stabilizing demand scenario paint a less drastic future picture of the global steam coal market as in the increasing demand scenario. In Figs. 13 and 14 we see that the regional flow shifts are similar that in the Current Polices scenario but they are less extreme and occur later in time. This can be seen for example in the fact that Colombia still supplies Europe with 23 Mt in 2030 and has not diverted all its supplies to Asia, as in the previous scenario. From a global perspective, we see in Fig. 15 that global consumption remains constant after 2015. Interestingly, global trade remains important and rises from a share of 16% to 18% due to the fact that India and China rely significantly on imports to satisfy their coal demand. Imports from these two countries is multiplied by 9.5 whereas imports from other countries decrease by 30% thus making the share of China and India in the global trade even higher than in the increasing demand scenario after 2015 to reach 56% in 2030. India's domestic production increase constantly from 2006 to 2030 whereas in China domestic production reaches a peak in 2020 an decrease after to be replaced by cheaper imports this again highlights the importance of global market.

Prices also add to the picture of a less strained global coal market in the stabilizing demand scenario. We still observe a very steep rise in domestic Indian prices but only to reach a level of 78 USD/t instead of 117 USD/t in the previous scenario. Also the global price level for imports is around 60 USD/t in 2030 more than 10 USD/t lower than in the increasing demand scenario for the same year.

Another output of the model that can be analyzed is the evolution of the supply costs influenced by production and investments, as described in Section 3.2. Fig. 16 shows the resulting FOB supply costs in 2020. If we compare with the starting values in Fig. 5 we can see some significant increases in production costs in Queensland, Australia, Russia, South Africa, Indonesia and China.

5.4. Results comparison with Hubbert-method based models

In the introduction we discussed three papers using methods derived from the Hubbert model. Fig. 17 provides a comparison of our modeling results (black curves) with the projections of Mohr and Evans [37] for bituminous coal (gray curves), a coal quality that covers most of the steam coal used in COALMOD-World. Patzek and Croft [39] and Höök et al. [20] only provide results for all coal types which makes a comparison with our results more difficult. In Fig. 17 the plain gray Hubbert Linearisation curve illustrates the issues associated with the use of the standard Hubbert curve method based only on historical production data: we see an overestimation of production around the peak period that exceeds any demand projections and then a sharp decline. The dotted and dashed gray line shows the results of a more refined model that takes into account supply and demand as well as reserves and cumulated production for the dotted line whereas the dashed line represent the authors best guess. These projections do not show such a sharp decline of production as in the Hubbert linearization case but production still peaks before 2020 and declines to levels lower than our projections. The results of Mohr and Evans [37] are driven by historical production data, which we have shown to be problematic in the introduction of this paper, and to a certain extend reserve estimations. Reserve estimates of coal are problematic as discussed by Höök et al.[20] as they are not done as thoroughly and frequently as for other resources and assessment methods and definitions vary between countries. This causes upward and downward corrections and jumps in the estimates that should however not be interpreted as signs of

Table 5
Data assumptions for the per 5-years capacity expansion limitations in Mtpa.

	Production capacity limitation	Export capacity limitation
US	276	20
Colombia	22	20
Venezuela	10	10
Poland	14	5
Ukraine	7	10
Russia	51	40
South Africa	47	15
India	63	
Indonesia	51	10
China	292	10
Australia	44	30

Table 4
Data and assumptions for the endogenous cost mechanism.

Country	Model producers	Mining basin type	Intercept increase	*mc_slp_var_f*	*mc_int_var*$_f$
US	P_USA_PRB	2	Slow	-1×10^{-6}	0.02
	P_USA_Rocky	2	Moderate	-1×10^{-6}	0.04
	P_USA_ILL	3	Moderate	0	0.04
	P_USA_APP	3	High	0	0.06
Colombia	P_COL	2	Slow	-1×10^{-5}	0.05
Venezuela	P_VEN	1	High	1×10^{-2}	0.2
Poland	P_POL	3	Slow	0	0.05
Ukraine	P_UKR	3	Moderate	0	0.2
Kazakhstan	P_KAZ	2	Moderate	-1×10^{-4}	0.1
Russia	P_RUS	2	Slow	-2×10^{-5}	0.05
South Africa	P_ZAF	3	Moderate	0	0.1
India	P_IND_North	2	Moderate	0	0.07
	P_IND_Orissa	3	High	0	0.25
	P_IND_West	3	Moderate	0	0.15
	P_IND_South	3	Moderate	0	0.15
Vietnam	P_VNM	4	High	1×10^{-2}	0.3
Indonesia	P_IDN	2	Slow	-5×10^{-6}	0.05
China	P_CHN_SIS	2	Moderate	-2×10^{-8}	0.08
	P_CHN_Northeast	3	Moderate	0	0.1
	P_CHN_HSA	3	Moderate	0	0.18
	P_CHN_YG	3	Moderate	0	0.14
Australia	P_AUS_QLD	2	Slow	-2×10^{-3}	0.05
	P_AUS_NSW	2	Slow	-2×10^{-3}	0.05
Mongolia	P_MNG	1	High	1×10^{-3}	0.2
Mozambique	P_MOZ	1	High	1×10^{-2}	0.4

Table 6
Results of COALMOD-World: domestic trade flows in Mtpa for the increasing demand and the stabilizing demand scenarios.

Scenario		Increasing demand						Stabilizing demand	
From	To	2006	2010	2015	2020	2025	2030	2020	2030
P_USA_PRB	C_USA_Rocky	63	104	104	104	104	98	104	102
P_USA_PRB	C_USA_Central	358	359	373	367	362	356	348	312
P_USA_PRB	C_USA_Gulf	70	166	166	167	167	167	163	178
P_USA_Rocky	C_USA_Rocky	40	9	12	10	10	14	7	
P_USA_ILL	C_USA_South	43	23	19	10	6	3	30	32
P_USA_ILL	C_USA_Gulf	70	85	85	90	90	90	70	62
P_USA_APP	C_USA_South	62	78	85	92	94	96	70	55
P_USA_APP	C_USA_East	58	57	59	58	57	57	56	48
P_USA_APP	C_USA_Gulf	79			0	13	11		
P_POL	C_POL	67	65	59	55	51	47	43	32
P_UKR	C_UKR	32	34	31	28	31	30	27	25
P_KAZ	C_KAZ	42	43	40	38	41	43	35	34
P_RUS	C_RUS_Siberia	70	96	94	88	92	96	79	78
P_RUS	C_RUS_Central	23	26	24	25	12	10	16	16
P_ZAF	C_ZAF	91	102	102	114	126	136	97	92
P_IND_North	C_IND_East	110	115	116	97	110	97	107	116
P_IND_North	C_IND_North	142	157	174	208	208	234	198	214
P_IND_Orissa	C_IND_East	0	9	26	84	41	86	60	55
P_IND_Orissa	C_IND_South	60	26	13					
P_IND_West	C_IND_West	60	58	57	56	55	54	40	33
P_IND_South	C_IND_South	21	37	18	38	29	36	27	30
P_VNM	C_VNM	3	2	1					
P_IDN	C_IDN	23	29	36	42	48	53	38	41
P_CHN_SIS	C_CHN_Northeast				13	24	35	4	
P_CHN_SIS	C_CHN_Main	339	429	518	553	593	626	492	505
P_CHN_SIS	C_CHN_Eastern	110	131	200	200	200	200	111	250
P_CHN_SIS	C_CHN_SIS	228	287	360	386	405	415	349	351
P_CHN_Northeast	C_CHN_Northeast	148	190	233	232	240	244	222	235
P_CHN_HSA	C_CHN_Eastern	100	157	157	193	193	193	252	
P_CHN_YG	C_CHN_South	248	297	273	267	257	252	267	247
P_MNG	C_MNG	0.15	0.13	0.13	0.20	0.25	0.28	0.20	0.34

increasing scarcity. In fact we do not see any reason why the market should be affected by a reserve constraint in the mid-term until 2030. The level of worldwide reserves has been constant at high levels for the last 25 years.[19] We also have to keep in mind that the definition of reserves is dynamic and that coal is underexplored in several world regions which increases the likelihood of substantial reserve additions in the next decades (see Minchener [36]).

5.5. Model evaluation and criticism

The "COALMOD-World" model uses 1671 single data inputs and is expressed by 6599 single equations that calculate values for 6599 single variables. It is programmed in GAMS using the mixed complementarity (MCP) format and the solver PATH [14]. The model solves in less than 10 s using a standard desktop computer (Pentium® Dual-core with 2.50 GHz CPU and 2.91 GB RAM). This rapidity allows for a very flexible use of the model for fast data update and test or for scenario or sensitivity analysis. The main weakness is the important amount of data input needed and the difficulty to find the appropriate data. Better access to experts and proprietary data could remedy these data issues.

6. Conclusions

In this paper, we present a tool for analysis of the future global steam coal market, the "COALMOD-World" model. From a starting point in 2006, we are able to give insights into how production and trade flows will develop until 2030, using two different scenarios for demand projection: one with a continuously increasing demand and one with a stabilizing demand. We are able to give a differentiated answer to the question about "the end of cheap coal?". Based on our model analysis, we find that it is not geological reserve depletion but capacity constraints as well as slow expansions of production and export capacities that could make coal more expensive in the future.

The resulting scarcity that starts appearing after 2015 can be measured in the model as a demand gap expressed by the percentage of the reference demand that is not satisfied. In the increasing demand scenario the gap represents 6.2% of the demand in 2025 and 9.3% in 2030. In the stabilizing demand scenario these values are 3% and 4.7% for 2025 and 2030 respectively. We also calculated that in the increasing demand scenario 18.6% of the assumed reserves are depleted until 2030 and only 16.3% of the reserves in the stabilizing demand scenario.[20]

This makes "peak coal" a less imminent question than the issue of the investments in production and export capacity needed to satisfy future demand. In the increasing demand scenario we calculate that through 2025, 124.6 billion USD in production capacity investments are needed and, due to the high amount of imports, 6.6 billion USD of investments are needed in export port capacities. In the stabilizing demand scenario 84.8 billion USD in production capacity investements are required and only 2.4 billion USD for port capacity expansions.

We believe the "COALMOD-World" model to be a good tool of analysis for the future development of the world steam coal market. Significant amelioration could be done with the data part of the model. A multi-disciplinary approach between geologists, engineers and economists is crucial for a better understanding of the coal market and resource markets in general. In the future we would like to widen the range of our scenarios and explore more

[19] *Source*: data compiled by the World Energy Council: http://www.worldenergy.org/.

[20] In both scenarios four mining basins are completely depleted: Vietnam, Mongolia and the Chinese Henan province. Additionally, Venezuela hits its reserve constraint in the increasing demand scenario.

Table 7
Results of COALMOD-World: international trade flows in Mtpa for the increasing demand and the stabilizing demand scenarios (part 1/2).

Scenario		Increasing demand						Stabilizing demand	
From	To	2006	2010	2015	2020	2025	2030	2020	2030
P_USA_APP	C_CAN	16	16	17	16	16	16	15	13
P_COL	C_USA_Gulf	21	19	27	15			31	
P_COL	C_MAR		1	5	6	7		5	5
P_COL	C_PRT		5	5	4	4		3	
P_COL	C_ESP		7	17	15	14		12	
P_COL	C_GBR	21	29	24	20	2		3	
P_COL	C_DEU	24	23	17	12				
P_COL	C_ITA			6	12	5		12	2
P_COL	C_TUR							3	6
P_COL	C_CHN_Eastern								
P_COL	C_KOR					11	54		10
P_COL	C_JPN				32	87	79	8	54
P_COL	C_TWN						10		
P_VEN	C_ESP		10						
P_VEN	C_NFB	9							
P_VEN	C_ITA			10	4	8			
P_VEN	C_TUR				4			9	3
P_VEN	C_ISR							1	7
P_VEN	C_IND_West					8	14		
P_VEN	C_CHN_Eastern						2		
P_POL	C_GBR	23	21	22	23	24	35	28	24
P_POL	C_NFB								
P_POL	C_DNK								4
P_KAZ	C_RUS_Siberia	5							
P_KAZ	C_RUS_Central	30	30	30	25	43	48	30	30
P_RUS	C_MAR						7		
P_RUS	C_PRT						3		2
P_RUS	C_ESP						12		9
P_RUS	C_GBR					13	0	2	
P_RUS	C_NFB	14	22	21	19	17	16	15	11
P_RUS	C_DEU	11	10	13	16	26	23	22	16
P_RUS	C_DNK	8	8	7	7	6	6	5	0
P_RUS	C_FIN	10	10	9	8	7	7	6	5
P_RUS	C_ITA						13		7
P_RUS	C_TUR	15	15	17	12	16	14		
P_RUS	C_ISR			5	21	27	33	15	15
P_RUS	C_UKR						1		
P_RUS	C_IND_West						5		
P_RUS	C_CHN_Eastern					12	60		
P_RUS	C_KOR	4	18	25	45	48		25	25
P_RUS	C_JPN	15							
P_ZAF	C_MAR	5	4						
P_ZAF	C_PRT	5							
P_ZAF	C_ESP	19							
P_ZAF	C_GBR	7							

restrictive climate policy scenarios as well as national policy scenarios.

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Appendix A. Mathematical formulation of the model

The profit maximization problem described in Sections 3.2, 3.3, 3.4 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:

$$0 \leqslant \left(\frac{1}{1+r_f}\right)^a \cdot \left[-p_{ac} + \frac{\partial C^P_{af}}{\partial x_{afc}} + trans\_c_{afc} \cdot \kappa_{af}\right] + \alpha^P_{af} \cdot \kappa_{af} + \frac{5}{2} \cdot \alpha^{Res}_f \cdot \kappa_{af} + \alpha^{Tcap\_c}_{afc} \cdot \kappa_{af} \perp x_{afc} \geqslant 0 \quad (24)$$

$$0 \leqslant \left(\frac{1}{1+r_f}\right)^a \cdot \left[-p_{ae} + \frac{\partial C^P_{af}}{\partial y_{afe}} + trans\_e_{afe} \cdot \kappa_{af}\right] + \alpha^P_{af} \cdot \kappa_{af} + \frac{5}{2} \cdot \alpha^{Res}_f \cdot \kappa_{af} + \alpha^{Tcap\_e}_{afe} \cdot \kappa_{af} \perp y_{afe} \geqslant 0 \quad (25)$$

$$0 \leqslant \left(\frac{1}{1+r_f}\right)^a \cdot \frac{CPinv_{af}}{5} - \sum_{a'>a} \alpha^P_{af} + \alpha^{Pinv}_{af} \perp Pinv_{af} \geqslant 0 \quad (26)$$

$$0 \leqslant \left(\frac{1}{1+r_f}\right)^a \cdot \frac{CTinv\_c_{afc}}{5} - \sum_{a'>a} \alpha^{Tcap\_c}_{afc} + \alpha^{Tinv\_c}_{afc} \perp Tinv\_c_{afc} \geqslant 0 \quad (27)$$

Table 8
Results of COALMOD-World: International trade flows in Mtpa for the increasing demand and the stabilizing demand scenarios (part 2/2).

Scenario		Increasing demand						Stabilizing demand	
From	To	2006	2010	2015	2020	2025	2030	2020	2030
P_ZAF	C_ITA	19	19						
P_ZAF	C_TUR	4	4						
P_ZAF	C_ISR	13	16	11					
P_ZAF	C_IND_West		21	28	48	56	58	51	64
P_ZAF	C_IND_South		24	47	56	76	81	57	67
P_ZAF	C_THA								
P_ZAF	C_MYS			16	13		8	9	17
P_VNM	C_CHN_South	20	20						
P_IDN	C_IND_West	16							
P_IDN	C_IND_South	15							
P_IDN	C_THA	7	8	10	11	12	13	10	11
P_IDN	C_MYS	13	16		3	24	11	8	
P_IDN	C_CHN_Eastern	11							
P_IDN	C_CHN_South		22	154	202	193	206	156	199
P_IDN	C_KOR		50						
P_IDN	C_JPN	20	7						
P_IDN	C_TWN	58	73	40				41	6
P_IDN	C_PHL	8	9	12	8			12	13
P_CHN_SIS	C_KOR	60		26					
P_AUS_QLD	C_CHN_Eastern								9
P_AUS_QLD	C_CHN_South						0		
P_AUS_QLD	C_KOR								3
P_AUS_QLD	C_JPN	57	60	31				30	
P_AUS_QLD	C_TWN			42	86	97	100	44	81
P_AUS_NSW	C_CHN_Eastern					20			85
P_AUS_NSW	C_CHN_South					57	86		
P_AUS_NSW	C_KOR			12	17			30	
P_AUS_NSW	C_JPN	13	35	73	63			47	
P_AUS_NSW	C_TWN				1	2			
P_AUS_NSW	C_PHL				4	13	14		
P_MNG	C_RUS_Siberia	2							
P_MNG	C_CHN_Main		5	22	30	33	33	35	36
P_MNG	C_CHN_SIS		5	5	5	10	15	5	9
P_MOZ	C_MAR								
P_MOZ	C_PRT								
P_MOZ	C_ESP	0.11							
P_MOZ	C_GBR	1							
P_MOZ	C_ITA		0.05						
P_MOZ	C_TUR								
P_MOZ	C_ISR		0						
P_MOZ	C_IND_West				0.03			1	6
P_MOZ	C_IND_South		0	3	7	8	13	6	8
P_MOZ	C_THA								
P_MOZ	C_MYS				3		5	1	2

$$0 \leqslant Pcap_f - \sum_{a'<a}\left[\left(\sum_c x_{afc}\cdot\kappa_{af} + \sum_e y_{afe}\cdot\kappa_{af}\right)\cdot mc\_int\_var_f\right] + \sum_{a'<a} Pinv_{af} - \left(\sum_c x_{afc}\cdot\kappa_{af} + \sum_e y_{afe}\cdot\kappa_{af}\right) \perp \alpha^P_{af} \geqslant 0 \tag{29}$$

$$0 \leqslant Pmaxinv_{af} - Pinv_{af} \perp \alpha^{Pinv}_{af} \geqslant 0 \tag{30}$$

$$0 \leqslant Res_f - \sum_{a\in A}\left[\left(\sum_c x_{afc}\cdot\kappa_{af} + \sum_e y_{afe}\cdot\kappa_{af} + \sum_c x_{(a-1)fc}\cdot\kappa_{(a-1)f} + \sum_e y_{(a-1)fe}\cdot\kappa_{(a-1)f}\right) * \frac{5}{2}\right] \perp \alpha^{Res}_f \geqslant 0 \tag{31}$$

$$0 \leqslant Tcap\_c_{fc} + \sum_{a'<a} Tinv\_c_{afc} - x_{afc}\cdot\kappa_{af} \perp \alpha^{Tcap\_c}_{afc} \geqslant 0 \tag{32}$$

$$0 \leqslant Tcap\_e_{fe} + \sum\nolimits_{a'<a} Tinv\_e_{efc} - y_{afe}\cdot\kappa_{af} \perp \alpha^{Tcap\_e}_{afe} \geqslant 0 \tag{33}$$

$$0 \leqslant Tmaxinv\_c_{afc} - Tinv\_c_{afc} \perp \alpha^{Tinv\_c}_{afc} \geqslant 0 \tag{34}$$

$$0 \leqslant Tmaxinv\_e_{afe} - Tinv\_e_{afe} \perp \alpha^{Tinv\_e}_{afe} \geqslant 0 \tag{35}$$

$$0 \leqslant mc\_int_{af} = mc\_int_{(a-1)f} + mc\_slp_{(a-1)f} \cdot \left(\sum_c x_{(a-1)fc}\cdot\kappa_{(a-1)f} + \sum_e y_{(a-1)fe}\cdot\kappa_{(a-1)f}\right) \cdot mc\_int\_var_f, \quad mc\_int_{af}\ \text{(free)} \tag{36}$$

$$0 \leqslant mc\_slp_{af} = mc\_slp\_start_f + mc\_slp\_var_f \cdot \sum_{a'<a} Pinv_{a'f}, \quad mc\_slp_{af}\ \text{(free)} \tag{37}$$

- Exporters KKTs:

$$0 \leqslant \left(\frac{1}{1+r_e}\right)^a \cdot [-p_{ac} + p_{ae} + Cport_{ae} \cdot \kappa_{ae} + searate_{aec} \cdot \kappa_{ae}] + \mu^E_{ae} \cdot \kappa_{ae} \perp z_{aec} \geqslant 0 \tag{38}$$

$$0 \leqslant \left(\frac{1}{1+r_e}\right)^a \cdot \frac{CEinv_{ae}}{5} - \sum_{a'>a} \mu^E_{ae} + \mu^{Einv}_{ae} + \mu^{Emax}_e \perp Einv_{ae} \geqslant 0 \tag{39}$$

$$0 \leqslant Ecap_e + \sum_{a'<a} Einv_{ae} - \sum_c z_{aec} \cdot \kappa_{ae} \perp \mu^E_{ae} \geqslant 0 \tag{40}$$

$$0 \leqslant Emaxinv_{ae} - Einv_{ae} \perp \mu^{Einv}_{ae} \geqslant 0 \tag{41}$$

$$0 \leqslant maxcap_e - Ecap_e - \sum\nolimits_a Einv_{ae} \perp \mu^{Emax}_e \geqslant 0 \tag{42}$$

- Producers quality factor:

$$\kappa_{af} = \kappa_f + \delta_f \cdot \sum\nolimits_{a' \leqslant a} \left(\sum\nolimits_c x_{afc} + \sum\nolimits_e y_{afe}\right), \quad \kappa_{af} \ (\text{free}) \tag{43}$$

- Final demand equation:

$$p_{ac} - p_{ac}\left(\sum\nolimits_f x_{afc}, \sum\nolimits_e z_{aec}\right) = 0, \quad p_{ac} \ (\text{free}) \tag{44}$$

- Market clearing condition:

$$0 = y_{afe} - \sum\nolimits_c z_{aec}, \quad p_{ae} \ (\text{free}) \tag{45}$$

- Chinese export restriction:

$$0 \leqslant China\_lic_{a\ E_{CHN}} - \sum\nolimits_{NoChina(c)} z_{aec} \cdot \kappa_{ae} \perp \pi_{a\ E_{CHN}} \geqslant 0 \tag{46}$$

This last restriction about the Chinese exports is a political restriction that limits Chinese exports through exports licenses. Due to its lesser relevance, it has not been addressed in the paper. It is only binding in 2006 at 60 Mt and then never again since China becomes a net importer in the future.

Appendix B. Nodes of COALMOD-World

Table 3.

Appendix C. Data of COALMOD-World

Tables 4 and 5.

Appendix D. Results of COALMOD-World

D.1. Domestic trade flows

Table 6.

D.2. International trade flows

Tables 7 and 8.

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