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Research Report

A model of the international steam coal market (COALMOD-World)

DIW Data Documentation, No. 85

Provided in Cooperation with:
German Institute for Economic Research (DIW Berlin)

DIW BERLIN

85

Data Documentation

Deutsches Institut für Wirtschaftsforschung 2016

A Model of the International Steam Coal Market (COALMOD-World)

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IMPRESSUM

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www.diw.de
ISSN 1861-1532

Data Documentation 85

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Abstract

Coal is at the core of the debate about climate change mitigation policies, yet the international market for it is not well represented in most energy models. This paper presents the COALMOD framework which is a model of the international steam coal market that can be readily used to explore implications of climate policies, but also to analyze market structure or to investigate issue of supply security. It features a detailed representation of both domestic and international steam coal supply, based on endogenously calculated Cost, Insurance, Fright (CIF) costs, and prices that take into account additional rents. It features endogenous investment into production, land transport, and export capacity, as well as an endogenous mechanism assessing production cost increase due to resource depletion. We provide a detailed model and data description and illustrate the features of the model by analyzing to scenarios derived from the IEA World Energy Outlook (New Policies and 450ppm scenario), highlighting the functionalities of the model.

Keywords: Future coal markets, Partial equilibrium modeling, International trade

JEL: C72, C69, L11, L71, Q41

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List of Abbreviations

Abbreviation	Description
CCTS	Carbon Capture, Transport, and Storage
CIF	Cost, insurance, freight
COALMOD	Dynamic partial equilibrium model of the world steam coal market
DERA	German Energy and Resource Agency (Deutsche Energie- und Rohstoffagentur)
DIW Berlin	German Institute for Economic Research (Deutsches Institut für Wirtschaftsforschung)
EIA	Energy Information Administration
FOB	Free on broad, costs include all cost incurred from the point of production to loading the coal on a ship ready for shipment.
GAMS	General Algebraic Modeling System
GSI	Geological Survey of India
IEA	International Energy Agency
KKT	Karush-Kuhn-Tucker
MCP	Mixed complementarity program
NBSC	National Bureau of Statistics China
NSWDPI	New South Wales Department of Primary Industries
IPCC	Intergovernmental Panel on Climate Change
PRB	Powder River Basin
OECD	Organization for Economic Cooperation and Development
PESD	Program on Energy and Sustainable Development
QLDDME	Queensland Department of Mines and Energy
SSP	Shared Socio-economic Pathways
TPED	Total Primary Energy Demand
VDKI	German Association of Coal Importers (Verein der Kohlenimporteure)

1 Introduction

Developing a structural model of international steam coal markets is a true challenge in an energy world at the crossroads, where the last years have been characterized by some fundamental structural changes and the future perspectives are unclear. On the one hand, there is a strong trend toward renewables in the OECD (Organization for Economic Cooperation and Development) countries, in particular in Europe but also in China, where climate change, and local pollution awareness has induced a number of climate policies. In parallel, the availability of cheap shale gas and low-cost wind and solar power have accelerated the decline of the coal industry in the US. On the other hand, South-East Asian countries have seen increasing demand for coal fueling their economic development. In a situation where the future role of coal in the global energy mix is put in question, projections of global coal demand exhibit a large spread, indicating fundamental uncertainties on its future development.[4]

Irrespective of the global demand trend, international coal trade has an important role to play in current and future global coal markets. Although the share of internationally traded coal in total world coal consumption is relatively small – approximately 15% (IEA 2013) – it has a major impact on the evolution of domestic markets and therefore plays a central role in the analysis. Some scholars argue by many scholars, international market prices are set by the arbitrage between Chinese coal delivered from the main production regions in the North to the consumption centers in the South-East versus coal imported to these demand centers (see e.g., Morse and He 2015).

When coal market modeling came back to the surface of the academic literature, after its first "boom" in the 1980s, coal markets had seen some stable years with continuous low prices, more or less competitive trading relations and a stable increase in seaborne trade (Haftendorn and Holz 2010). However, coal markets have been caught in the turmoil of a general energy price and cost increase since 2007. In 2008, they experienced a price peak similar to the oil markets (see Figure 1), and they compete with other mining sectors for qualified labor, mining services, and machinery, which has led to a substantial cost increase in many producing countries. The strong demand increase driven by Asia and the subsequent capacity expansions have led to a consistent cost escalation affecting the fundamentals of the coal markets. However, the last three years were characterized by plummeting prices, again. The two main driving factors behind this trend are overcapacity originating from overly optimistic demand projections, and a stark decline in oil price which makes up a significant part of production and transportation costs of coal (see Figure 1).

[4] The preparation of this document was facilitated by the participation of the authors in third party funded projects. Financial support was granted from Program on Energy and Sustainable Development (PESD) at Stanford University in the Global Coal Markets project (2010-2012), furthermore, financial support was provided in SECURE project granted under the Seventh Framework Programme funding scheme, as well as the RESOURCES project granted under German Federal Ministry of Education and Research "Economics of Climate Change" funding scheme (grant no. 01LA1135B, 2012-2015). Moreover, we thank Claudia Kemfert, Andreas Tissen, Philipp M. Richter, Kim Collins, Jan Ilsemann, and Josephine Logisch for contributing to model analysis, the data set and model development in the early phases. Daniel Huppmann and Pao-Yu Oei provided comments. The usual disclaimer applies.

With coal at the center of discussions between climate change mitigation policies and economic development, a model of the international steam coal market can deliver insights into the mechanics of the market and assess the implications of climate policy measures in a comprehensive manner. Besides, other issues like security of supply or market power abuse might gain importance again, underlining the need for a practical assessment tool. This report presents the functionalities of the COALMOD-World model (cf. Haftendorn, Holz, and Hirschhausen 2012; Holz et al. 2015) which replicates global patterns of coal supply, demand and international trade in great detail. It features endogenous investments in production and transportation capacities in a multi-period framework and represents the substitution relation between imports and domestic production of steam coal. It simulates production, trade, price, and capacity development and can readily be applied to discover policy implications through scenario analysis.

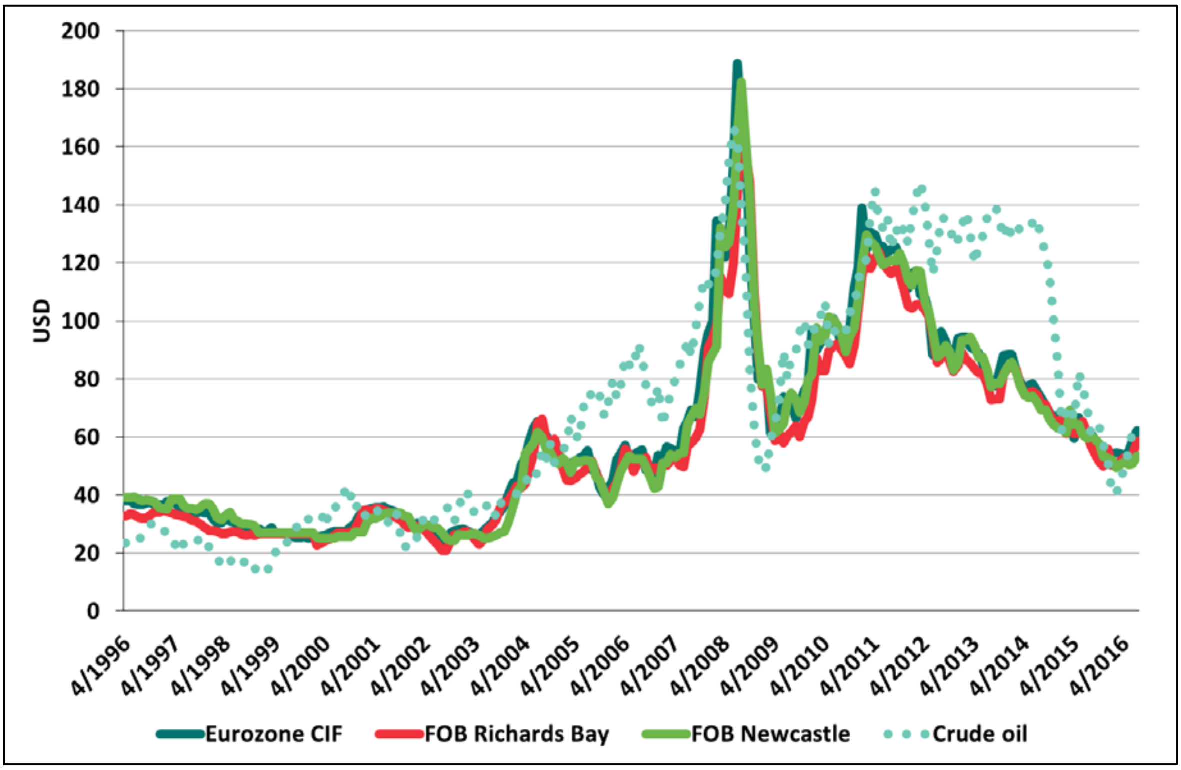


Figure 1: Monthly prices for steam coal in USD/t (CIF Eurozone, FOB Richards Bay, and FOB Newcastle) and crude oil in USD/bbl (crude oil index) between April 1996 and April 2016.

Source: HWWI commodity prices in the Thompson Reuters Datastream database.

The remainder of this report is organized as follows: the next section provides an introduction to the international steam coal market and gives an indication of the uncertainty about future demand. The evolution of the COALMOD modeling framework and how it is embedded in the literature on steam coal market models is given in Section 3. Section 4 provides a detailed description of the model structure and mathematical formulation. Section 5 presents input data including information on data sources. Using two scenarios, Section 6 illustrates the functionalities for the model. Section 7 discusses limitations of the model framework, and Section 8 concludes.

2 The international steam coal market

2.1 Types of coal

Coal is commonly categorized as steam coal, metallurgical coal or lignite, based on its material properties and end-use. Steam coal is the set of coal types that are typically combusted to produce steam[5]. In 2014, Around 70 per cent of steam coal was used to produce electricity and heat, and the remainder mostly for other industrial heat-consuming activities (IEA 2015b, III.68). IEA (2015b, I.25) defines steam coal as anthracite, other bituminous and sub-bituminous coal, with an energy content ranging from 20 GJ/t to as much as 30 GJ/t (IEA 2015b, I.25).

Steam coal is mined at either surface or underground mines, mainly depending on the depth of the coal seam (Speight 2012). The raw coal is processed through crushing, screening, and beneficiation/washing operations to meet customer specifications. To transport the coal to ports or markets, rail is most common, but river barges are also used (as well as other modes of transport over short distances). Where necessary along the supply chain, coal is stored in open air stockpiles or enclosed silos.

2.2 Coal markets

Large-scale demand for steam coal originated in the eighteenth and nineteenth centuries, where its use in powering steam engines was central to the industrial revolution and subsequent economic growth in Europe and the United States (Fernihough and O'Rourke 2014; Chandler 1972). By the beginning of the 20th century coal had become the dominant source of energy worldwide, though during the early to mid-20th century it lost shares to oil and gas (Smil 2000). The oil crises of the 1970s triggered the revival of the steam coal market, as countries which had previously imported large quantities of oil for power generation sought to bolster their energy security by diversifying their power supply (IEA 1997, 25). Coal was a substitute for oil due to its wide abundance and low cost (Thurber and Morse 2015, 12–13). From 1980 to 2000, steam coal consumption grew steadily in most OECD and non-OECD regions alike (with Europe being an exception), and from 2000 to 2005 there was a large spike in steam coal consumption in non-OECD countries, in particular in China and the rest of the Asia-Pacific region (IEA 2014a).

Table 1 provides an overview of major steam coal producers and consumers in 2014. Since 2005, steam coal consumption in the OECD has decreased by around 12% (IEA 2015b), due to general trends of decarbonization and lower energy consumption (IEA 2014b, 172). However, over that same period consumption has continued to grow in non-OECD countries – by 10 times the volume of the OECD decrease (IEA 2015b). This rapid growth in demand triggered significant investment in supply capacity and transport infrastructure (IEA 2014b, 186). However, in the past few years demand growth has slowed.

[5] Metallurgical coal is bituminous coal which is used to produce coke for use in the iron and steel industry. Lignite is a low-quality brown coal which is also used to produce steam.

Since the 1980s, China has been the world's largest consumer of steam coal. India was the world's third largest steam coal consumer since 1995, but since 2005 has almost doubled its consumption to become the world's second largest steam coal consumer in 2014 (on a tonnage basis) – narrowly overtaking the USA, whose consumption has decreased by around 20% over the past decade (IEA 2015b, III.30-III.32). Other large consumers of steam coal over the past two decades are South Africa, Japan and the Russian Federation; while in the 1970s and 1980s, Poland, the United Kingdom, and Germany were also in the mix. In more recent years, analysis by Steckel et al. (2015) shows that it is not only China and India which are driving a renaissance of coal; rather, it is gaining dominance in numerous developing countries, especially in South-East Asia but also in Turkey.

Table 1: Major steam coal producers and consumers in 2014.

Major producers in 2014	Major consumers in 2014
China (3,200 Mt)	China (3,280 Mt)
United States (770 Mt)	India (760 Mt)
India (560 Mt)	United States (750 Mt)
Indonesia (470 Mt)	South Africa (174 Mt)
South Africa (250 Mt)	Japan (137 Mt)
Australia (246)	Korea (100 Mt)
Russian Federation (190 Mt)	Russian Federation (77 Mt)
Kazakhstan (94 Mt)	Kazakhstan (67 Mt)
Colombia (84 Mt)	Poland (60 Mt)
Poland (61 Mt)	Indonesia (60 Mt)
World production 6,150 Mt	World consumption 6,090 Mt

Source: IEA (2015b).

The world's largest consumers of steam coal are also its largest producers. Since the mid-1980s (when it overtook the USA), China has produced the largest volumes of steam coal, followed by the USA. India has been the world's third-largest producer of steam coal since the 1990s, having overtaken South Africa (IEA 2015b, III.10-III.11). Along with Australia and the Russian Federation, these countries account for over 90% of world steam coal production – with China alone accounting for 52% of the total. Similar to consumption trends, Poland, the United Kingdom and Germany were historically large producers of steam coal, but by the 1990s had lost any significant market share.

Figure 2 depicts major importers, exporters and trade flows of steam coal in 2013 and 2014. Worldwide, the total quantity of internationally traded steam coal in 2014 represented 17% of total demand, with the majority being seaborne trade (IEA 2015b, III.39, III.44, III.49). The total volume traded has increased at an average annual rate of 6% between 1990 and 2014, and the proportion of seaborne trade increased at an average annual rate of 2% over the same period. For most of the 1990s and 2000s, Japan and Korea were the world's largest importers of steam coal. However, since the late 2000s, China, and subsequently India, overtook Japan as the world's largest importers. Indonesia, Australia, and the Russian Federation are the world's largest exporters of steam coal, followed by Columbia and South Africa. Due to their geographical location, South Africa, as well as Russia, are "swing suppliers", which export to both the Pacific and Atlantic regions according to market dynamics (IEA/OECD 2014, 50).

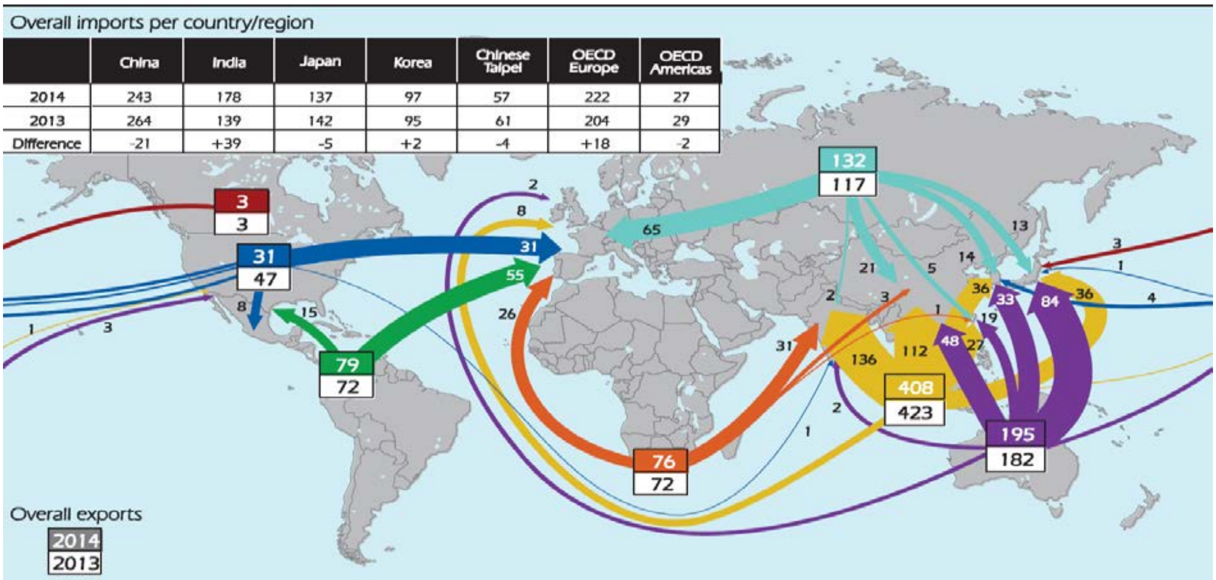


Figure 2: Major exporters, importers, and trade flows of steam coal in 2013 and 2014.

Source: OECD/IEA (2015) © IEA/OECD 2015 Medium-Term Coal Market Report, IEA Publishing. Licence: www.iea.org/t&c

2.3 Wedge of global institutional projections

To illustrate the uncertainty around future coal consumption, projections of total coal demand, including steam coal, metallurgical coal and lignite, from a range of institutions, energy companies, and scientific papers are shown in Figure 3, with historical data for the 2010 year included for reference.

Due to different base years and different specifications of the underlying models even for 2015 there is no consistent estimate provided by the various source, even though their reported figured are all in the range of 150-170 EJ. Starting 2020, there is a divergence of 70 EJ between the lowest and the highest estimate, which increases to 180 EJ, by 2040. The projections can be grouped into three categories:

- The highest estimates are provided by scenarios assuming no policy changes, and no international cooperation (IEA WEO CPS and Statoil – RIVS).
- The second group spans between estimates in the EIA IEO – RC and the Statoil – REFS. Scenarios in this range are referred to as reference scenarios or moderate policy scenarios by the publishing institutions and companies. Projections from BP, ExxonMobil and MIT, who only provide one scenario, fall in this range. They do not assume any ambitious climate change mitigation efforts and only a moderate transformation of energy systems towards renewable energy sources. These projections suggest coal demand stagnation around current consumption levels with a demand of 140-190 EJ in 2040. It is worth mentioning that BP, IEA WEO – NPS, and EIA IEO - RC still project a moderate increase in coal demand, while MIT, ExxonMobil, and Statoil - REFS see are peak in coal demand around 2030 and a mild decline after that.
- The third set of scenarios assumes a structural change in global energy system with strong emission reductions. In the case of IEA WEO 450ppm and M&E projections, these are even

claimed to be consistent with a 2°C target. Still there is a large divergence of 60 EJ, more than a third of current consumption, also for this set of scenarios.

The main reason for the disagreement is the crucial difference in the role that CCTS play in the respective future energy system. While the IEA WEO 450pmm scenario assumes that 75% of installed coal-fired power generation capacity is equipped with CCTS, M&E estimate coal consumption patterns that would result in the absence of this technology. Given substantial doubts whether the technology will ever enhance from or even achieve the demonstration phase (cf. Reiner 2016; Hirschhausen, Herold, and Oei 2012), the M&E scenario is the only one that projects a coal demand pattern which is robustly in line with the 2°C target.

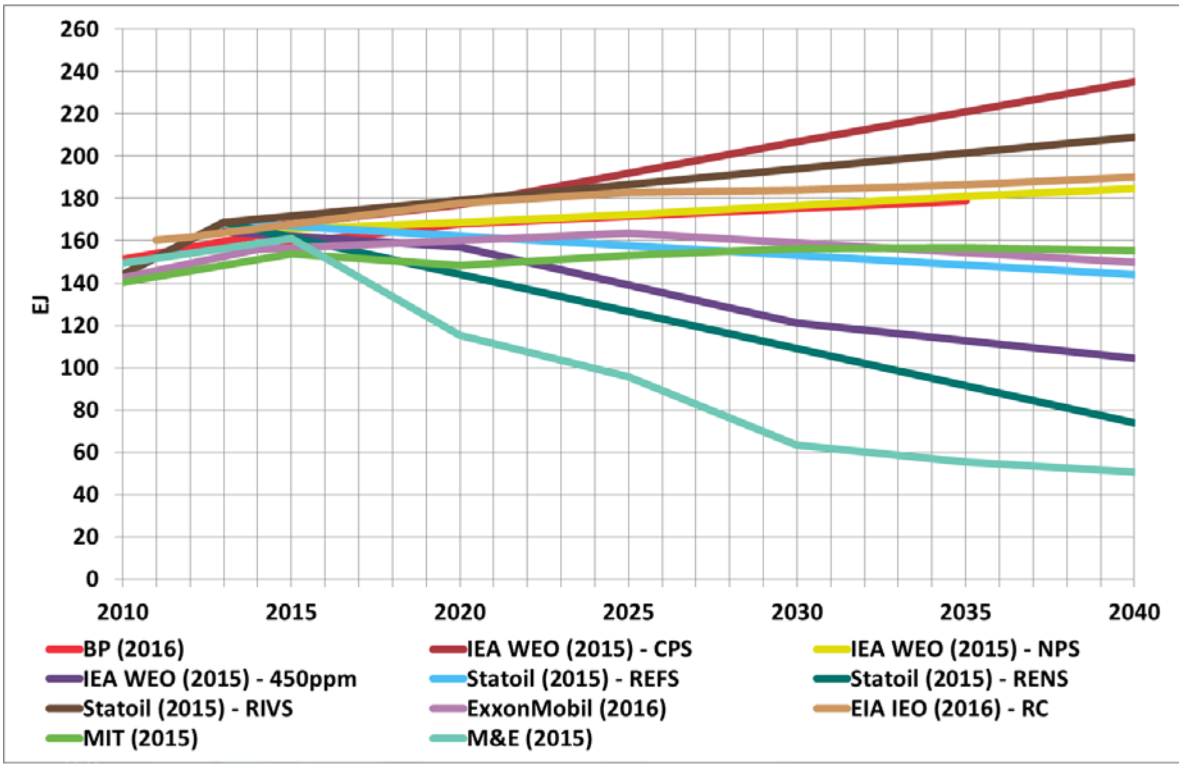


Figure 3: Projected coal demand until 2040 from various studies (in EJ).[7]

Source: Own illustration based on BP (2016), EIA (2016), ExxonMobil (2016), IEA (2015a), McGlade and Ekins (2015), MIT (2015), and Statoil (2016).

[7] The underlying models provide estimates in five to ten year steps, therefore the line between these steps are only for illustrative purposes. IEA WEO (2015) - CPS refers to the IEA World Energy Outlook's Current Policy Scenario (IEA 2015a), NPS stands for New Policies Scenario, and 450ppm is the 450 ppm scenario; Statoil - REFS refers to the Statoil World Energy Perspectives Reform Scenario (Statoil 2016), RENS to the Renewables Scenario, and RIVS to the Rivalry Scenario; EIA EIO – RC refers to the EIA Energy International Outlook's Reference Case (EIA 2016), and M&E refers to the extraction path for coal calculated to be consistent with a 2°C target by McGlade and Ekins (2015), excluding the option of CCTS.

3 Literature

3.1 State of the international literature

An extensive review of the – sparse – coal-market specific modeling literature until 2010 is provided in Haftendorn and Holz (2010) and Paulus and Trüby (2011). There were some early modeling efforts applied to the US and international coal markets in the 1970s and 1980s (see Shapiro and White 1982; Kolstad and Abbey 1984). Often, coal modules are part of larger energy system models, as in most of the models applied in the Energy Modeling Forum number 2, "Coal in transition 1980 – 2000" (EMF 1978). However, both the situation on the international steam coal market as well as modeling techniques have evolved since the 1980s. For other energy and resource markets, such as natural gas, multi-period models with endogenous investments have been developed during the 2000s (e.g., Hartley and Medlock 2006; Egging, Holz, and Gabriel 2010, for world natural gas markets).

Two modeling teams have been the major contributors to the recent renaissance of coal market modeling applying the equilibrium technique, coincidentally both from Germany where steam coal imports have traditionally had an important role: a team from Energiewirtschaftliches Institut an der Universität zu Köln (ewi), and the developers of the COALMOD framework. For the former, seminal papers are by Trüby and Paulus (e.g., 2012) who developed a one-period trade model to test the market structure until 2008. They also developed a multi-period model which they use to investigate the interaction between the Chinese and the world coal market (Paulus and Trüby 2011). A coal market model focusing only on Chinese coal supply was developed by Rioux et al. (2015).

3.2 Development of the COALMOD model framework and publications

The COALMOD model framework was developed and continuously extended by a joint team of researchers at the Department of Energy, Transport and Environment at DIW Berlin, in close cooperation with researchers from Berlin University of Technology (Workgroup for Infrastructure Policy, WIP). The first version was developed by Haftendorn and Holz (Haftendorn and Holz 2010). This version called COALMOD-Trade focused on steam coal exports, only, and calculated static market equilibria for 2005 and 2006, to access market structure and compare model specifications. The model was also introduced to a broader, non-academic audience in two articles, (in German, Haftendorn et al. 2011; Haftendorn et al. 2012)). Further model development was undertaken within the framework of the "Global Coal Market" project led by the Program on Energy and Sustainable Development (PESD) at Stanford University. PESD invited the modeling team Berlin to expand their model of the seaborne export market (Haftendorn and Holz 2010) into a comprehensive model of the global steam coal market that additionally includes national and regional trade flows. Haftendorn, Holz, and Hirschhausen (2012) presents COALMOD-World, which incorporates these features and constitutes a dynamic model of the international steam coal market with a 2030 horizon, and 2006 as the base year. Moreover, it introduces the sophisticated mine-mortality mechanism and depletion of reserves to the model. Holz et al. (2015) updates the base year of the model to 2010, taking into account major shifts in cost and demand. The model presented in this report is fundamentally based on Holz et al. (2015) with minor extension of global coverage and extending the model horizon to 2050.

The ongoing development and application of the COALMOD framework has led to a considerable number of publications. Haftendorn (2012) provides an overview of publications using the COALMOD modeling framework until 2012. Similarly, Haftendorn et al. (2013) summarizes scenario results obtained using the COALMOD-World model until 2013. Currently, there are two main strains of applications of the COALMOD framework:

- The first is concerned with analyzing the market structure of the steam coal market. The COALMOD-Trade model was set up to test for market power abuse in 2005 and 2006. Haftendorn and Holz (2010) in general find no evidence for market power exertion, but rather show evidence for spatial price discrimination. These findings are put into broader perspective in Haftendorn, Hirschhausen, and Holz (2008), adding the observation of increasing market concentration by a small number of dominant firms, and calling for close surveillance through regulatory authorities. The latter issue is further investigated by Haftendorn (2012). The paper explores the hypothesis that the incumbent dominant firms located in South Africa and Colombia withheld supply to the European market in 2004 and 2005, which allowed a new entrant, namely Russia in the market. Findings suggest that market power was exerted but no collusion between the incumbents was detected.
- The second strain is concerned with the effect of short-term and long-term policy and other shocks to the market. Hirschhausen et al. (2011) COALMOD-Trade model was used to examine the issue of security of supply in Europe. They find little risk from supply disruption and market power exertion. Haftendorn, Kemfert and Holz (2012) use COALMOD-World to examine interactions between climate policies and the global steam coal market until 2030. They examine a unilateral European climate policy which is found to induce high leakage. By contrast, a supply-side policy like an Indonesian export-limiting is reported to be most effective in an environment of low intensity of global climate policy when the market is constrained. A third scenario investigates a fast-roll out of Carbon Capture, Transport, and Storage (CCTS). If the technology is realized, increased demand due to reduced efficiency can lead to additional positive climate effects, if the market is constrained. A different approach is taken by Richter, Mendelevitch, and Jotzo (2015), who explore the complementarity between export taxes and climate change mitigation. They find that only for large coalitions of exporters the double dividend of market power rents and significant reduction in CO_2 emissions from steam coal use can be realized, while for smaller coalition there is high leakage. A moderate global CO_2 tax can achieve the same outcome but comes with different distributional implications. Mendelevitch (2016b) focuses on the effect of supply-side climate policies on the steam coal market. For the removal of coal producer subsidies it finds only insignificant reductions in coal-based CO_2 emissions. By contrast, a moratorium on new coal mines is found to have a substantial impact on future coal consumption, coming with the side-effect of increased prices which can offset foregone profits from new mines. Mendelevitch (2016a) provides an overview of various supply-side climate policy scenarios and applications performed with the COALMOD framework.

4 The COALMOD-World model

4.1 Overview

COALMOD-World is a multi-period model that simulates market outcomes, trade flows, and prices for the period 2010 to 2040 in five year steps, as well as investments in the coal sector value chain. The model assumes profit-maximizing players who optimize their expected and discounted profit over the total model horizon. The model result is a cost-efficient outcome that abstracts from the short-term real world frictions and cycles but gives a valuable indication of future trends.

The value chain of the steam coal sector will be reflected in the model setup. Various types of players are 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 small companies, usually operating in one country only. Transport infrastructure in the production countries 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 utilized by multiple companies. Traders as intermediaries also play a role in this market that is characterized by bilateral relationships; they can be vertically integrated or contractually connected to every stage of the industry.

4.2 Model structure

COALMOD-World is a multi-period equilibrium model of the global steam coal market with two types of players: producers and exporters facing consumers represented by a demand function. The stages of the real-world value chain that are included in the model are represented in Figure 4 by small rectangles inside the larger producer and exporter boxes. Coal import terminals and the subsequent land transport links to the final consumers are excluded because their capacities are assumed to be sufficient. By assumption, demand for seaborne import coal is situated 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 also pays for the seaborne transport. All players are aggregated on a national or regional (subnational) level.

The 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 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 synonymously. 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 only be supplied domestically. 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.

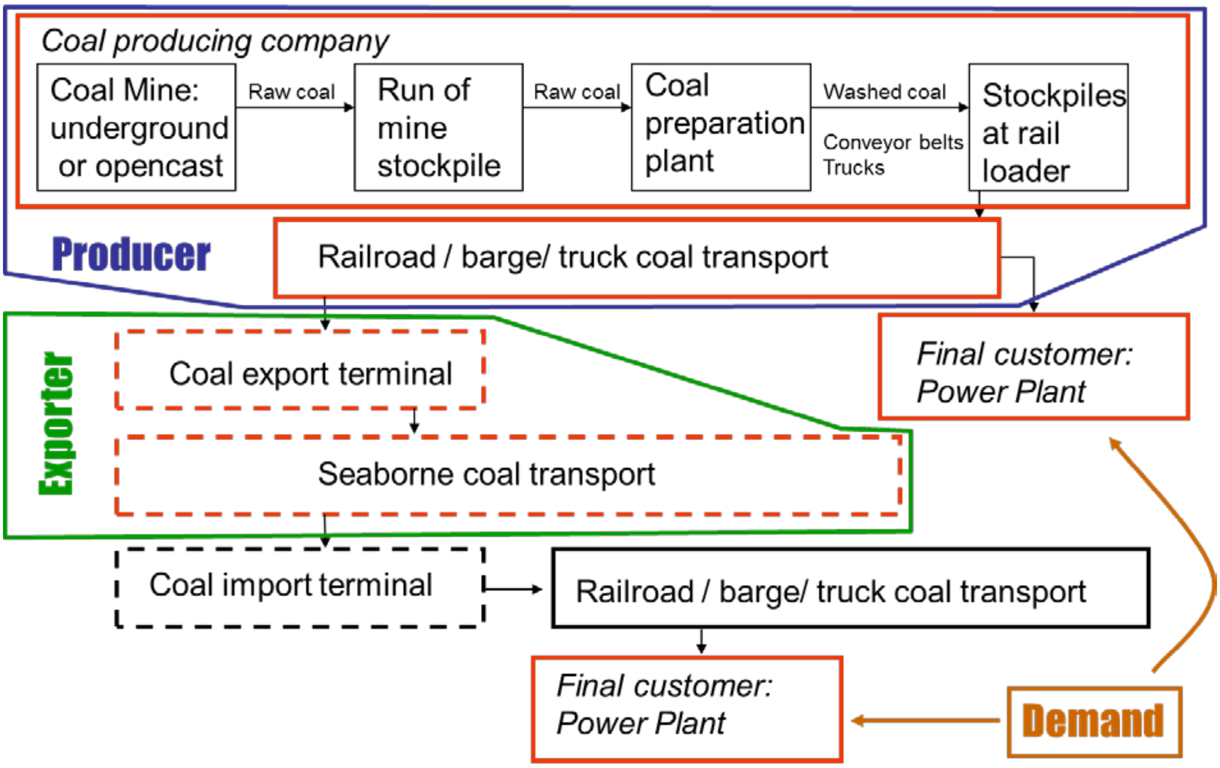


Figure 4: Model players in the steam coal value added chain.

Figure 5 shows the model structure and the relationships between producers, exporters and demand. The producers extract and treat (i.e., produce) the coal under some production capacity constraint. They can sell it either to local demand nodes or to linked exporters. They bear the production and the inland transport costs. Further, they can invest in additional production capacities and in transport capacities to local demand or to the exporter. These investments are, in turn, also subject to constraints. Moreover, a constraint on reserves is applied over the total model horizon. Shadow prices (dual variables) are obtained for all constraints and may indicate an incentive to expanding capacities.

In the same logic as the producers, the exporters maximize their profit. Each exporter is linked to a maximum of one producer. The profit for each year is defined by the revenue from sales net of the costs of purchasing the coal at the FOB price from the producer, the costs of operating the export terminal, the costs of transport (shipping) to the final market and finally the potential costs of investing in additional export capacity. An exporter can only sell to a demand node with a port. Since each model exporter has a dedicated model producer, the energy content factor of the exporter is equal to the energy content of the producer that supplies it for any given year.

Final demand is located at a consuming node and represented by a linear inverse demand function, that is, a marginal willingness to pay function. Individual demand functions for each demand node are constructed using respective reference prices and reference demand values for the model starting year 2010 and using demand growth projections for future years. Moreover, we make assumptions about the demand elasticities. The producers can be in indirect contact with the final demand through their exporter or sell directly to their domestic demand. Prices are expressed in USD per GJ because we concentrate on the demand for energy embodied in the coal.

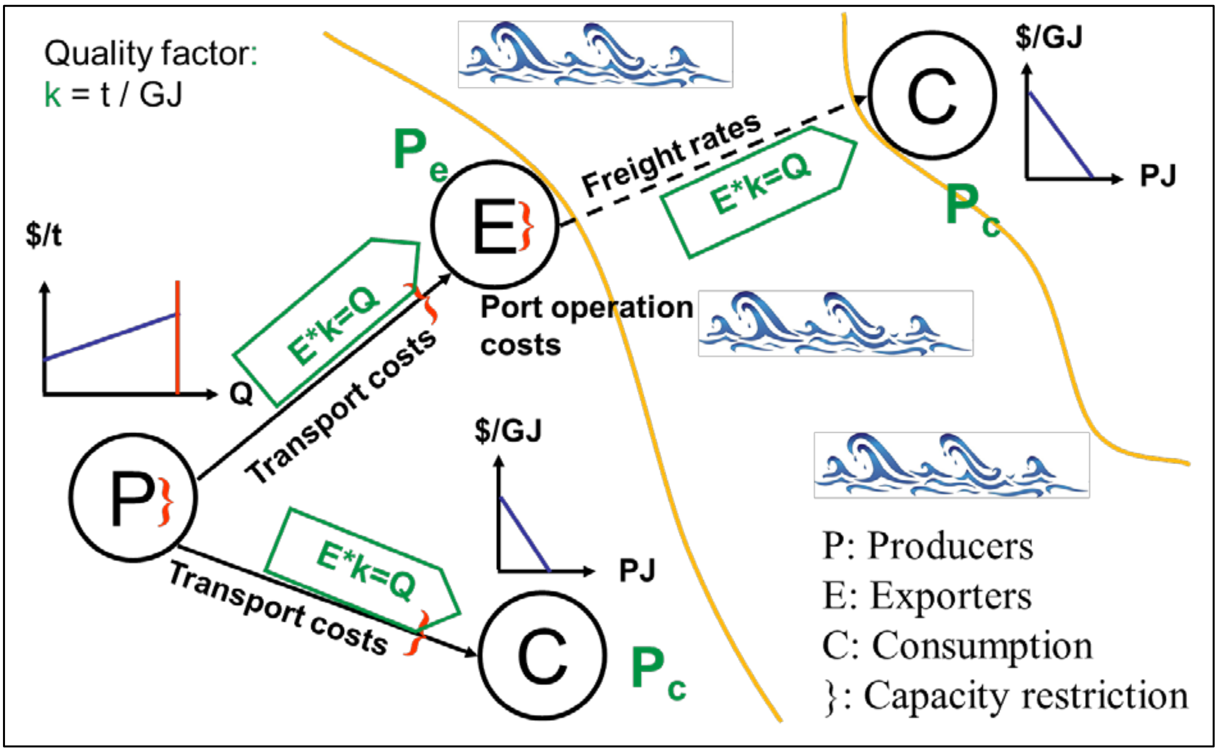


Figure 5: COALMOD-World model structure.

The model runs until 2040 and calculates yearly equilibria for the energy quantities sold in the years 2010, 2015, 2020, 2025, 2030, 2035, and 2040, which can be called "model years." Also, the players can decide on investments in each model year that will be available in the next model year.[8] Thus, the model does not only calculate an equilibrium within each model year but also over the total model horizon regarding optimal investments. For the years between the model years (e.g., for 2011, 2012, 2013, 2014, between 2010 and 2015), we interpolate 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

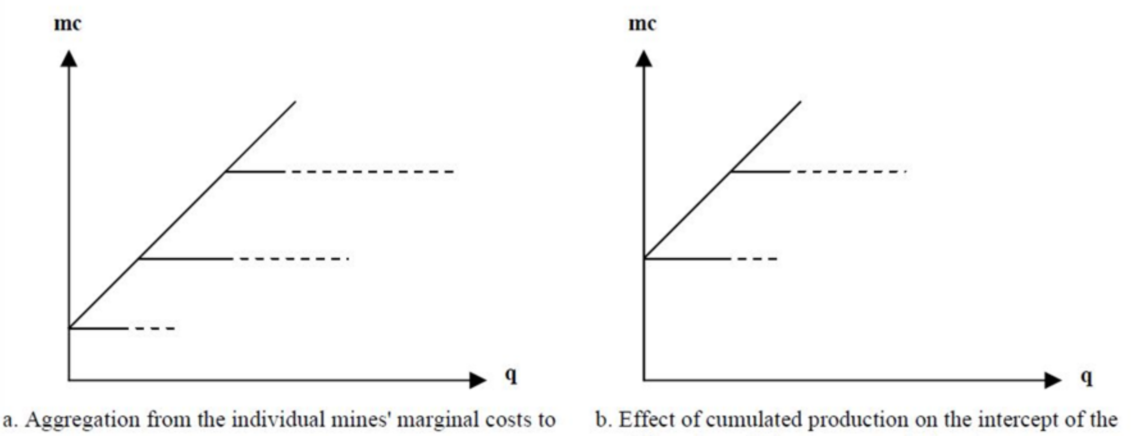
[8] Although equilibria are actually calculated until 2050, we interpret the results only until 2040 because of a risk of distortion of the investment results given the short payback period after 2040.

perfect information 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.

It is important to note that the traded quantities are the quantities of energy contained in the coal and expressed in petajoules (PJ). 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 to mass using a conversion factor in tons per gigajoule (GJ) that varies by producer (see Figure 5).

We assume short-run production cost functions for a year for each producer that can vary over time. Until recently, resource market models have often used the same short-run costs for every model period (e.g., Egging, Holz, and Gabriel 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, Hobbs, and van Oostvoorn 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.

a 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 curve in one period we add the production capacities on the q-axis and connect them with their respective marginal costs on the mc-axis.



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.

Figure 6: Production cost mechanism for a model producer node.

After this static consideration, let us consider how this cost function might evolve over time. This effect of cumulated production is illustrated in b. 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. This is due to the fact that the cheapest mines are usually the deposits that are the easiest to access and are, hence, the oldest ones in operation. The effect of cumulated production from one model period to another is then that the cheapest mines are mined out and that the cheapest producer in a disappears from the cost curve. We call this effect "mine mortality".

Mine mortality causes the intercept of the cost function to increase as shown in b. The mine mortality factor gives the position on the cost curve of the previous period to determine the new intercept. Graphically, this is the passage from a to b. If the mine mortality factor is equal to one (i.e., the mine mortality rate is equal to 100%) it means that the cumulated production leads to a complete depletion of the oldest, cheapest mines. This may happen 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.[9] Since the slope of the cost curve indicates the relation of cheap and more expensive mines in the production region, the slope is the second factor in determining the new intercept's position.

4.3 Mathematical formulation

4.3.1 Sets, parameters, and variables

Table 2, Table 3 and Table 4 provide a full nomenclature of all sets, parameters and variables used in the model. Furthermore, Table A.1 in Appendix A gives the full list of model producers, exporters and consumers, including their geographic correspondence.

Table 2: List of sets in the COALMOD-World model.

Set name	Description	Range
a	model year	[2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050]
c	consumer	see Table A.1
e	exporter	see Table A.1
f	producer	see Table A.1

Table 3: List of parameters in the COALMOD-World model.

Parameter name	Description	Unit
cap_e^E	initial export capacity of exporter e	[Mt/a]
cap_f^P	initial production capacity of producer f	[Mt/a]
cap_{fc}^{TC}	initial transport capacity from producer f to consumer c	[Mt/a]
cap_{fe}^{TE}	initial transport capacity from producer f to exporter e	[Mt/a]
$China\_lic_{aE_{CHN}}$	Chinese export license volume	[Mt/a]

[9] For the coal sector, in which reserve assessments are sparse, another direction of the change of the cost function intercept is possible: the intercept could decrease due to the discovery and opening of lower-cost mines. In Haftendorn et al. (2012), we discuss this possibility and propose an extended endogenous cost mechanism. Moreover, technological progress in coal extraction methods could reduce costs over time even in existing mines. However, we lack empirical data to include these mechanisms for cost decreases in the model structure.

$Cinv_{ae}^{E}$	investment cost for export capacity expansion for exporter e	[USD/t]
$Cinv_{af}^{P}$	investment cost for producer capacity expansion for producer f	[USD/t]
$Cinv_{afc}^{TC}$	investment cost for transport capacity expansion from producer f to consumer c	[USD/t]
$Cinv_{afe}^{TE}$	investment cost for transport capacity expansion from producer f to exporter e	[USD/t]
fee_{ae}	port handling fee for exporter e	[USD/t]
$\overline{inv}_{ae}^{E}$	maximum export capacity expansion of exporter e	[Mt/a per 5 year period]
$\overline{inv}_{af}^{P}$	maximum production capacity expansion of producer f	[Mt/a per 5 year period]
κ_e	energy content of coal shipped by exporter e	[t/GJ]
κ_f	energy content of coal produced by producer f	[t/GJ]
$mc\_int\_start_{af}$	slop of marginal cost curve for producer f	USD/t
$mc\_int\_var_{af}$	intercept variation factor (mine mortality rate)	USD/t
$mc\_slop\_start_{af}$	starting value of marginal cost intercept for producer f	USD/t
$plength$	period length	5 years
r_e	discount factor applied by exporter e	[%]
r_f	discount factor applied by producer f	[%]
res_f	resource endowment of producer f	[Mt]
$searate_{aec}$	freight rate for transport from exporter e to consumer c	[USD/t]
$trans_{afc}^{C}$	transportation cost from producer f to consumer c	[USD/t]
$trans_{afe}^{E}$	transportation cost from producer f to exporter e	[USD/t]

Table 4: List of variables in the COALMOD-World model.

Variable name	Description	Unit
$a_{afc}^{cap^{TC}}$	shadow price of transport capacity constraint from producer f to consumer c	[USD/t]
$a_{afe}^{cap^{TE}}$	shadow price of transport capacity constraint from producer f to exporter e	[USD/t]
$a_{af}^{inv^{P}}$	shadow price for maximal production capacity expansion constraint for producer f	[USD/t]
α_{af}^{P}	shadow price of production capacity constraint for producer f	[USD/t]
α_{f}^{res}	shadow price of resource constraint	[USD/t]
inv_{ae}^{E}	investment in export capacity by exporter e in period a	[Mt/a]
inv_{af}^{P}	investment in production capacity by producer f in period a	[Mt/a]
inv_{afc}^{TC}	investment in transport capacity from producer f to consumer c in period a	[Mt/a]
inv_{afe}^{TE}	investment in transport capacity from producer f to	[Mt/a]

	exporter e in period a	
p_{ac}^{C}	price paid by consumer to exporter or producer	[USD/GJ]
p_{ae}^{E}	price paid by exporter to producer	[USD/GJ]
τ_{a}^{E}	export-based tax	[USD/GJ]
τ_{a}^{P}	production-based tax	[USD/GJ]
x_{afc}	Sales from producer f to consumer c	[GJ/a]
y_{afe}	Sales from producer f to exporter e	[GJ/a]
z_{aec}	Sales from exporter e to consumer c	[GJ/a]

4.3.2 A producer's problem

The producer maximizes its profit under reserve constraints and technical restrictions on its production and land transport capacity in every year.

In the first 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. The second line of (1) shows the production cost function in an undefined form. The third line of (1) represents the transport costs to local demand and exporters. Line four of (1) calculates the total investment costs in production capacity and line five does the same for the investments in transport capacities to local demand and exporters.

$$\begin{aligned}
&\max_{x_{afc};\, y_{afe};\, inv_{af}^{P};\, inv_{afc}^{TC};\, inv_{afc}^{TE}} \quad \Pi_f^P(x_{afc}; y_{afe}; inv_{af}^{P}; inv_{afc}^{TC};\ inv_{afc}^{TE}) = \\
&\sum_{a\in A}\left(\frac{1}{1+r_f}\right)^a \cdot [\sum_c p_{ac}^{C}\cdot x_{afc} + \sum_e p_{ae}^{E}\cdot y_{afe} \\
&-C_{af}^{P}\left[x_{afc}, y_{afe}\right] \\
&-\sum_c trans_{afc}^{C}\cdot \kappa_f \cdot x_{afc} - \sum_e trans_{afe}^{E}\cdot \kappa_f \cdot y_{afe} \\
&-Cinv_{af}^{P}\cdot inv_{af}^{P} \\
&-\sum_c Cinv_{afc}^{TC}\cdot inv_{afc}^{TC} - \sum_e Cinv_{afe}^{TE}\cdot inv_{afe}^{TE}]
\end{aligned} \tag{1}$$

s.t.

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

$$\overline{inv}_{af}^{P} - inv_{af}^{P} \geq 0 \qquad \left(\alpha_{af}^{inv^P}\right) \tag{3}$$

$$\begin{aligned}
&res_f - \sum_{a\neq startyear} [(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \\
&+\sum_c \kappa_f \cdot x_{(a-1)fc} + \sum_e \kappa_f \cdot y_{(a-1)fe}) \cdot \frac{plength}{2}] \geq 0 \qquad \left(\alpha_f^{res}\right)
\end{aligned} \tag{4}$$

$$cap^{TC}_{fc} + \sum_{a'<a} inv^{TC}_{afc} - \kappa_f \cdot x_{afc} \geq 0 \qquad \left(\alpha^{cap^{TC}}_{afc}\right) \tag{5}$$

$$cap^{TE}_{fe} + \sum_{a'<a} inv^{TE}_{afe} - \kappa_f \cdot y_{afe} \geq 0 \qquad \left(\alpha^{cap^{TE}}_{afe}\right) \tag{6}$$

$$x_{afc} \geq 0; y_{afe} \geq 0; inv^{P}_{af} \geq 0; inv^{TC}_{afc} \geq 0; inv^{TE}_{afe} \geq 0 \tag{7}$$

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). Equation (4) is the reserve constraint of the producer over the total model period and includes reserve utilization from production in years between the modeled 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. The symbols in parentheses are the dual variables associated with the constraints and (7) are the non-negativity constraints of the decision variables.

$$\begin{aligned} &mc\_int_{af} = mc\_int_{(a-1)f} \\ &+mc\_slp_{(a-1)f} \cdot \kappa_f \cdot mc\_int\_var_f \cdot \left(\sum_c x_{(a-1)fc} + \sum_e y_{(a-1)fe}\right), \\ &mc\_int_{af} \ \ (free) \end{aligned} \tag{8}$$

The endogenous cost mechanism that enters the model is given in (8). The equation 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 mine mortality factor $mc\_int\_var_f$ determines how fast the cheapest mines are mined out.

4.3.3 An exporter's problem

The exporter maximizes its profit under technical restrictions on export capacity in every year.

In the first line of the exporter's objective function (9) 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 term after the brackets is the revenue from sales to consumers. The second line of (9) shows the costs incurred by the exporter. First, coal has to be purchased from a producer. Next, port fee and freight rate need to be covered. Then investment costs for capacity expansion can arise.

$$\begin{aligned} &\max_{z_{aec};inv^E_{ae}} \quad \Pi^E_e(z_{aec}; inv^E_{ae}) = \sum_{a\in A}\left(\frac{1}{1+r_e}\right)^a \cdot \Big[\sum_c p^C_{ac} \cdot z_{aec} \\ &-\sum_c p^E_{ae} \cdot z_{aec} - \sum_c fee_{ae} \cdot \kappa_e \cdot z_{aec} - \sum_c searate_{aec} \cdot \kappa_e \cdot z_{aec} - Cinv^E_{ae} \cdot inv^E_{ae}\Big] \end{aligned} \tag{9}$$

s.t.

$$cap_e^E + \sum_{a'<a} inv_{ae}^E - \sum_c \kappa_e \cdot z_{aec} \geq 0 \quad \left(\mu_{ae}^E\right) \tag{10}$$

$$\overline{inv}_{ae}^E - inv_{ae}^E \geq 0 \quad \left(\mu_{ae}^{inv^E}\right) \tag{11}$$

$$z_{aec} \geq 0; inv_{ae}^E \geq 0 \tag{12}$$

Constraint (10) 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 (11) expresses the maximum investments in export capacity for one model period. The symbols in parentheses are the dual variables associated with the constraints.

Modeling China's export restriction requires an additional equation. 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 (13). $China\_lic_{aE_{CHN}}$ represents the level of Chinese export licenses for a given year in million tons.

$$China\_lic_{aE_{CHN}} - \sum_{NoChina(c)} z_{aec} \cdot \kappa_{ae} \geq 0 \quad \left(\pi_{aE_{CHN}}\right) \tag{13}$$

4.3.4 Market clearing

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

$$p_{ac}^C - p_{ac}^C\left(\sum_f x_{afc}, \sum_e z_{aec}\right) = 0 \quad , p_{ac}^C \textit{ (free)} \tag{14}$$

Moreover, equation (15) clears sales of the producer to the exporter. Its dual variable gives the price at which the exporter receives the coal from the producer, p_{ae}^E.

$$0 = y_{afe} - \sum_c z_{aec} \quad , p_{ae}^E \textit{ (free)} \tag{15}$$

5 Model specification and input data

In section 4.2 we introduced the concepts of nodes and model players. The model simulates the market on an aggregated basis in that we do not include individual mines or coal-fired power plants separately. However, the spatial characteristics of the market and the associated transport costs make it necessary to define aggregated nodes in the different producing and consuming countries. Section 5.1 describes our choice of model countries and nodes, and then we provide a detailed overview of our data in subsequent sections. The data collection required a major effort since there is no central source available. We generally collected data from publicly available sources; however, there is scarcity of data in the public domain and improvements could be achieved by using more detailed data. In order to remove inconsistencies in the data and to properly represent the base year 2010 we carried out a calibration of the data. Thereby, 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 6.

5.1 Countries and nodes definition

We include all countries that were either consuming at least 5 million tons per annum (Mtpa) or producing and exporting at least 5 Mtpa in 2010, at the time of the development of the model. Some additional countries that are becoming relevant players on the global market are included too (e.g., Mongolia and Mozambique). The world map in Figure 7 shows the represented countries, indicating their role on the world steam 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 and 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 and demand node; this is the case for the US, China, India, and Australia. The complete list of countries and nodes in the model can be found in Table A.1 in the Appendix.

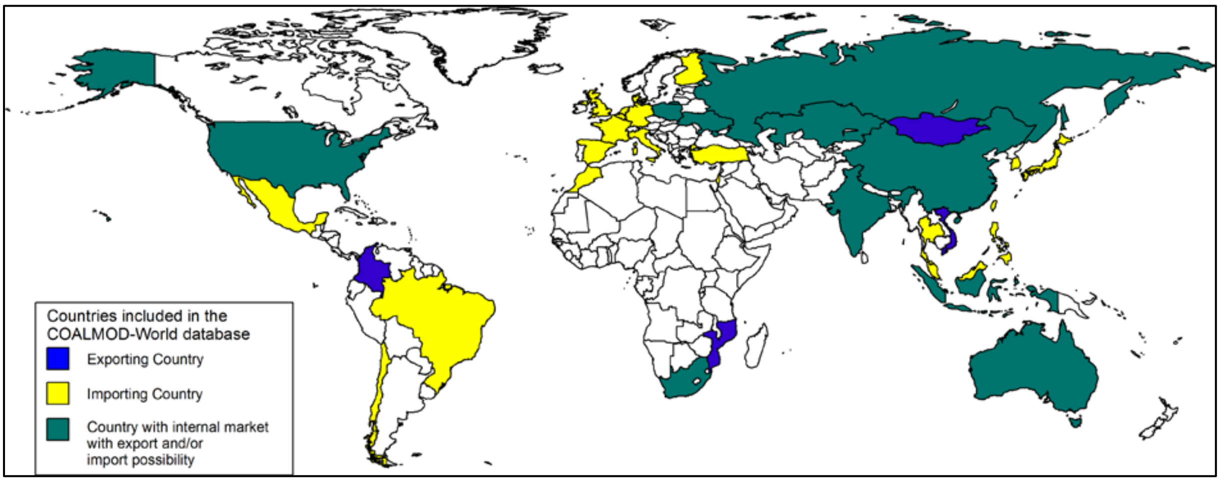


Figure 7: Countries included in the COALMOD-World database.

Producing nodes are generally defined by mining basins that are restricted by geological realities. The location of power plants is more dispersed as it relates to human settlement patterns. This makes it more difficult to locate our consuming nodes. For the consumers that can only be reached via an import harbor 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.

5.2 Production, costs, and reserves

The cost data is based on Baruya (2007) as well as several recent IEA sources and publications by the German Association of Coal Importers (VDKI). For each export country, Baruya (2007) provides estimates for the low and high average costs; the other sources usually follow the same methodology. This information is used to construct the producers' cost functions for the base year. We assume that the average low and high costs also represent unit costs for the cheapest and the most expensive 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.

In we depict the marginal cost curves for the base year 2010. 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 the world market, while some Chinese regions (Shanxi, Shaanxi, Inner Mongolia – abbreviated SIS), the Powder River Basin (US), and South Africa are on the lower end.

Clearly, there has been a substantial cost escalation in the last years that is evident when comparing to our earlier 2006 base year (Haftendorn, Holz, and Hirschhausen 2012). However, this cost increase did not hit all producers in the same way and proportionally across regions. While some producers such as Australia and also Indonesia have experienced substantial cost increases, others like the US Powder River Basin have almost maintained their costs of four years earlier. This has led to a shift in the relative cost structure: for example, with increasing export capacities (c.f. Figure 11) Powder River Basin coal is competitive with all other producers in all consuming regions, while the more expensive Australian coal is only competitive to ship within its Pacific home region (see, e.g., IEA 2011; VDKI 2013).

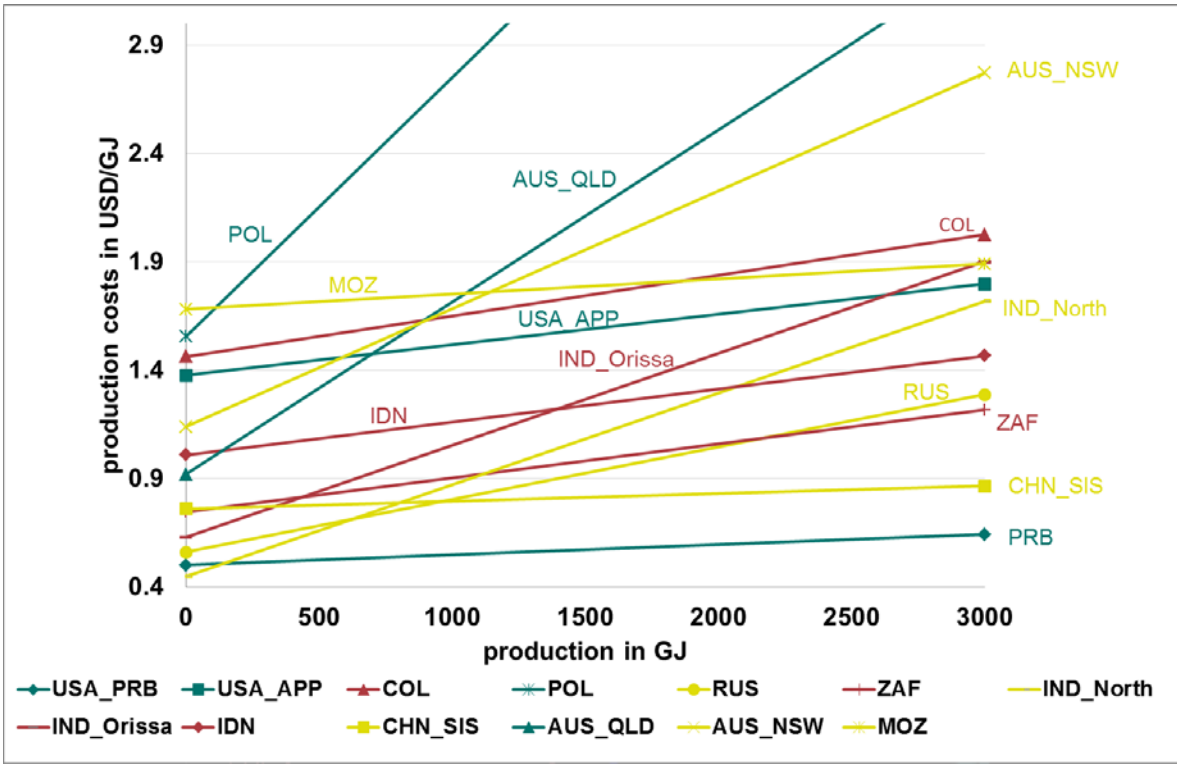


Figure 8: Marginal cost curves (2010) for selected production nodes (in USD/GJ).

Source: Authors' work based on EIA (2012, table 32); NSWDPI (2009); QLDDME (2009); Rademacher (2008); Baruya (2007); NBSC (2007); Ritschel and Schiffer (2007).

For the producers from the CIS (Russia, Kazakhstan, and Ukraine), Colombia, Venezuela, South Africa, and Indonesia, the cost data and the parameters of the marginal cost function as well as the capacities are updated based on IEA (2011). Countries with more than one production node require more detailed data on production capacities.[10] This data is used to build a merit order curve of costs using production data for each model producer and so estimate the producers' cost functions. In order to determine the cost functions in the long run, some assumptions had to be made about mine mortality in each five-year period and the associated rate of growth in the intercept. Table A.2 in the Appendix shows these assumptions and the values of the intercept and slope for each producer.

The investment costs are a major input to the multi-period model since they determine the 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 (OECD and IEA 2008). 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. But investment costs in Australia can also exceed 100 USD/tpa if the project includes new transport and washing facilities.

Table 5: Assumed production capacity expansion limitations per five-year period (in Mtpa).

Country	Production expansion limitation (Mtpa)	Country	Production expansion limitation (Mtpa)
Russia	51	Poland	5
Ukraine	10	Kazakhstan	15
Venezuela	10	Colombia	30
China	450	Mongolia	20
Vietnam	10	Indonesia	90
Australia	40	India	110
Mozambique	15	South Africa	40
USA	224		

We therefore assign values from 40 to 80 USD/tpa to the different producers' investment costs for production capacity based on information about the country and mine mortality rates. The assignment is based on factors such as the prevalent type of mining, geology, and the state of technology. Unit investment costs and the production capacity for the base year and every production node are shown in Figure 9.

[10] For the United States, EIA (2012) gives production information; for China, data comes from the NBSC (2007); for India, from Indiastat (2012, Spreadsheet "Average Cost of Production of Coal") and Indian Bureau of Mines (20112012, in the chapter title "Prices"); and for Australia, updated data from Rademacher (2008, 78), Bayer (2012), NSWDPI (2009), and QLDDME (2009) are used. For Vietnam, the production capacity is taken from Rademacher (2008); 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).

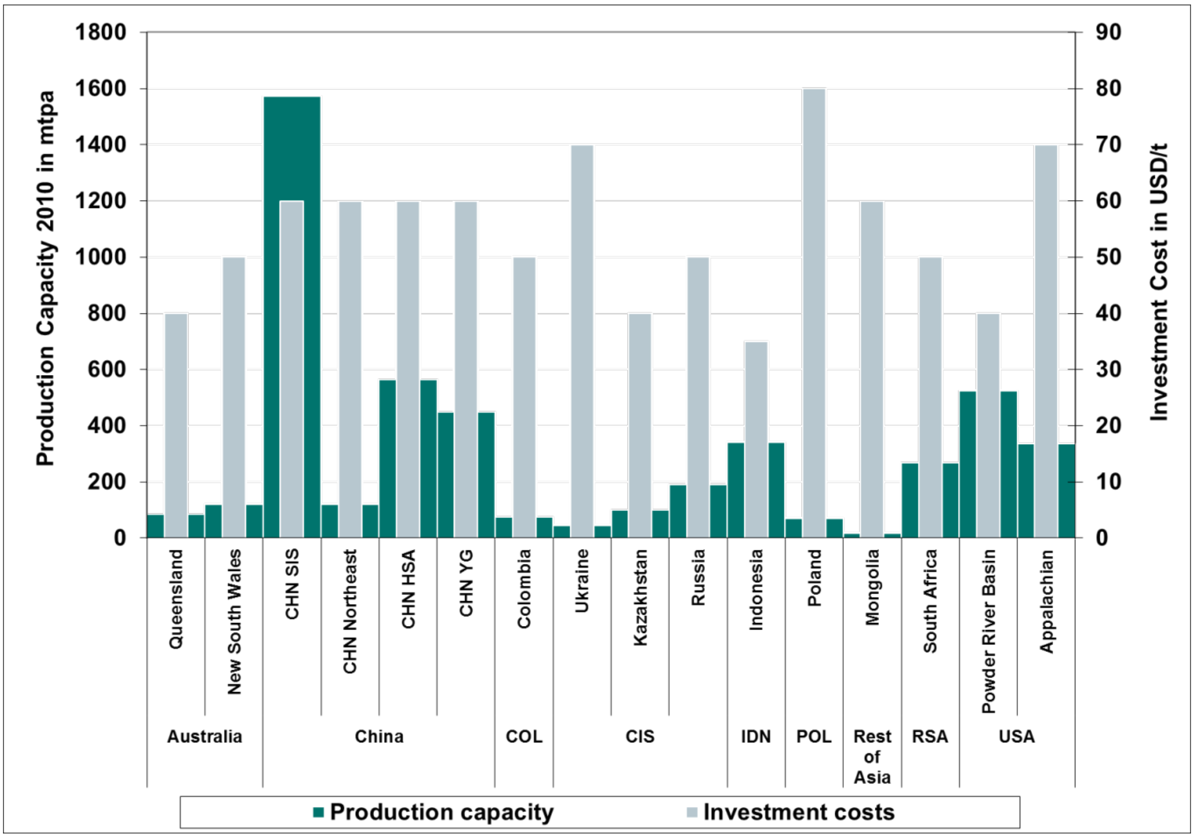


Figure 9: Capacity and investment costs for all production nodes in the base year.

Source: Authors' work based on IEA and OECD (2008) and Rademacher (2008).

Investments are restricted per period; this restriction reflects the players' limited ability to add more production capacity (and also export capacity, see below). The data in is based on historical data and country reports, such as Eberhard (2015) and Lucarelli (2015). For all countries with several nodes, the value gives the aggregate of all producing nodes.

Another important parameter for a multi-period model is the discount rate 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. In 2013 the data base reported 10.3% of the US coal industry. While this value is currently down to 5.7%, we believe that this is due to macroeconomic fluctuations, given the global value is at 9.0%.[11] For convenience and to account for the additional uncertainty that is inherent in the market due to glooming climate policies we assume a 10% discount rate for exporters and producers.

Producers may, in theory, be limited by their available reserves, and we want to be able to capture possible incentives for producers to modify their behavior in reaction to constrained reserves. We follow the standard definition of reserves from 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

[11] See http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.htm (accessed on January 27, 2010).

raw form) under present and expected local economic conditions with existing available technology" (EIA 2008).

In Figure 10 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 (EIA 2008, table 8.2) but complement it with other sources for some individual nodes (e.g., DERA 2012). This data is aggregated on a national level; thus to get the distribution on a sub-national level other sources had to be used. For the US, EIA data (2008, table 15) was used; the reserve distribution for the Indian production nodes is based on GSI (2010) and that for the Chinese producers on NBSC (2007).

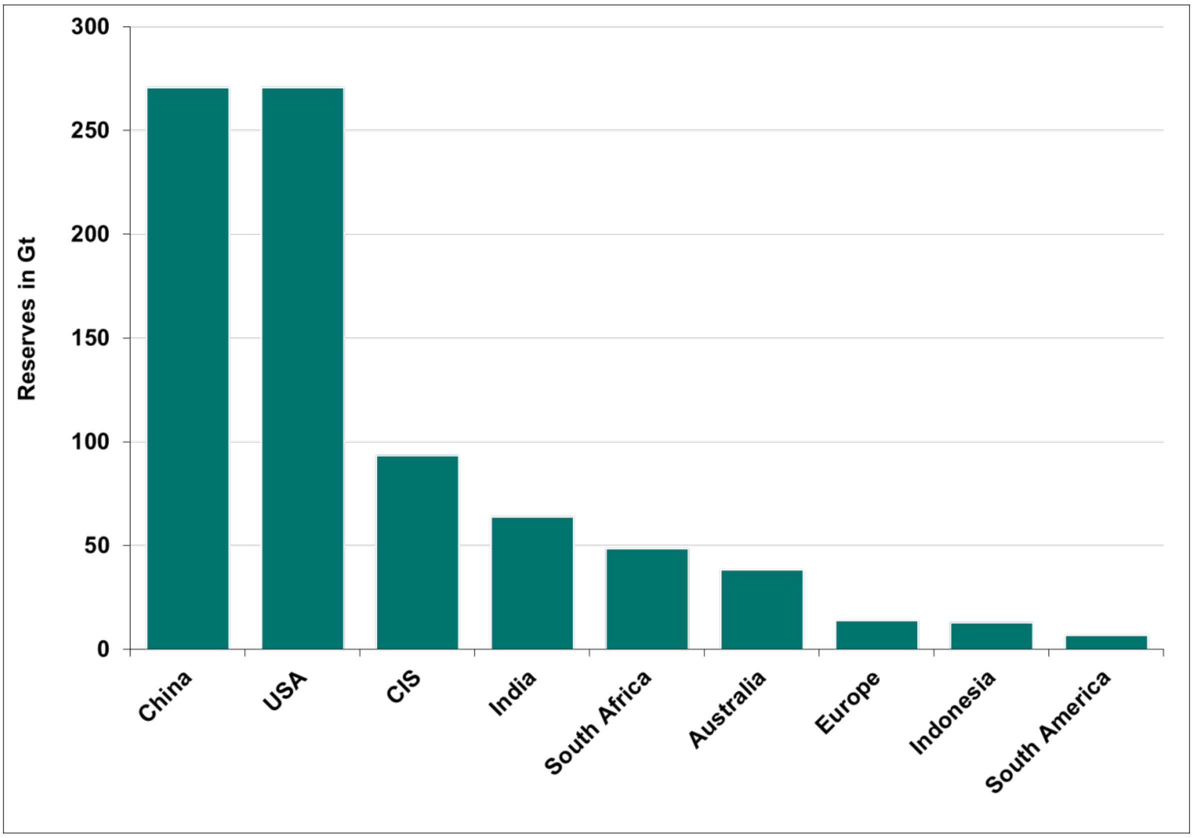


Figure 10: Reserves of major countries in COALMOD-World (in Gt).

Source: Authors' work based on DERA (2012), EIA (2008), GSI (2010), and NBSC (2007).

Using a static reserves number is, of course, a limitation of our analysis, since real world observations show that the reserve assessments in the coal sector are sparse and often limited in geographical scope. Indeed, as a result of a large available reserve base and of costly exploration, the new delineation of resources that may potentially be mineable reserves is generally sluggish (Rogner et al. 2012). No structural analysis of "resource to reserve" conversion of the coal sector is available in the literature to our knowledge. However, since we do not want to neglect this fundamental aspect of production of a non-renewable resource, we opt for including regional reserve numbers.

The coal quality data is shown in Table 6.[12] The Energy Watch Group (2007) provides evidence that coal quality is generally decreasing over time as 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. The model captures some of this effect through the different coal qualities of the producers of the larger countries. For example, if the recent developments in the US continue with more (lower grade) coal from the Powder River Basin being produced, the overall quality of US coal will decrease.

Table 6: Energy content of coal by production node.

Node	Calorific value in kcal/kg	Energy content in GJ/t
USA PRB	4781	20.004
USA Rockies	6338	26.516
USA Illinois	6226	26.051
USA Appalachia	6949	29.075
Colombia	6375	26.673
Venezuela	6375	26.673
Poland	6300	26.359
Ukraine	6200	25.941
Kazakhstan	6000	25.104
Russia	6400	26.778
South Africa	6400	26.778
India North	4717	19.737
India Orissa	4187	17.520
India West	5209	21.793
India South	4866	20.360
Vietnam	7000	29.288
Indonesia	5450	22.803
China SIS	6597	27.600
China Northeast	5154	21.565
China HSA	6118	25.598
China YG	6074	25.413
Australia Queensland	6500	27.196
Australia New South Wales	6300	26.359
Mongolia	6100	25.522
Mozambique	6400	26.778

Source: Authors' work based on Platts (2009), Indian Bureau of Mines (2012), Ritschel and Schiffer (2007), and Tewalt et al. (2010).

5.3 Land transport

Land transport costs and capacities are associated with the transport from a producer to either a local demand node or to an exporter. In case of transportation to a demand node, the center of the demand region is used to calculate the distance; in the case of an exporter, the location of the main harbor is used. Land transport represents mainly transport by train but can also include road transport on trucks and in certain cases river transport by barges or overland conveyor belts. The transport costs are assumed to be constant over time and the capacities can be expanded by investments.

[12] Coal quality data is based on Platts (2009) for the US, Colombia, Venezuela, Poland, Russia, South Africa, Indonesia, and Australia. For China, it is based on Tewalt et al. (2010), and for India on Indian Bureau of Mines (2012, chapter titled "Coal and Lignite"). For Vietnam the quality data is taken from Ritschel and Schiffer (2007).

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 US, data for the transport costs is based on EIA (2011) for the transport costs. The transport capacities inside the US are determined using actual flow data given in EIA (EIA 2011, Spreadsheet “Domestic Distribution of U.S. Coal by Origin State, Consumer, Destination and Method of Transportation”). The land transport cost data for the CIS is from Crocker and Kovalchuk (2008) as well as IEA (2011) 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 Indiastat (2012, Spreadsheet “Railway Freight on Coal in India”). Investments in additional overland transport capacity are set in a range between 10 and 55 USD/tpa depending on distance, landscape and topography, and if the project is mostly greenfield or not.

5.4 Export ports

The data for the export ports includes the export capacity in the starting year and the port handling costs as well as the investment costs and investment limits per five-year period. For mathematical reasons, in the complementarity modeling format, we need to include a separate exporter for each producer in each exporting region. The coal of the dedicated exporter has the same calorific value as the producer and, thus, avoids the so-called “pooling problem” of mixing coals of different qualities. This way, we have, for example, an exporter “PRB” (Powder River Basin) next to an exporter “Rockies” at the West Coast of the U.S. We needed to decide on the allocation of the total available capacities to these two export players. Similarly, where steam coal and coking coal exports use the same harbor facilities we had to decide on the capacity available to steam coal exports (e.g., in Australia). These decisions were taken case-by-case keeping in mind that capacities included in 2010 can be used at relatively low costs throughout the model’s time horizon without bearing investment costs for capacity expansions.

Cost data for most regions is based on Baruya (2007). For Colombia, the CIS, South Africa, and Mozambique, the capacity data in the starting year is taken from IEA (2011; 2012c). For Venezuela the costs are assumed to be similar to Colombia, and the capacities are determined using relevant export data. For the United States, the capacity data comes from VDKI (2012) as well as company information. VDKI (2011) provided information on Australia. Chinese port capacities are provided by the NBSC (2007). The costs for Poland are taken from Ritschel and Schiffer (2007) and the capacity is based on export data. Investment costs for additional export capacity are set between 10 and 30 USD/tpa depending on the country and the preexisting infrastructure. Data on allowed maximum expansion per five-year period is mostly from VDKI (2008; 2011) and IEA (2011). Figure 11 shows the unit costs of expanding export capacity together with the exporting harbor capacity in the base year.

Constraints in export capacity expansion are particularly notable in global trade patterns. As above for the production investment limitations, the data in is based on historical data and country reports, such as Eberhard (2015) and Lucarelli (2015). For all countries with several nodes, the value gives the aggregate of all export ports. This means in particular that in the US (a country with four producing regions and three export ports, each possibly having several dedicated producers) the individual export limitation is lower. For example, the US West exporter has a total expansion possibility of 35 Mtpa per five-year period, but the PRB exporter via the West Coast has only 30 Mtpa investment capacity, the other 5 Mtpa of allowed investments being allocated to the US Rockies.

Table 7: Assumed export capacity expansion limitations per five-year period (in Mtpa).

Country	Export expansion limitation (Mtpa)	Country	Export expansion limitation (Mtpa)
Russia	65	Poland	5
Ukraine	10	USA	115
Venezuela	10	Colombia	40
China	50	Australia	108
Indonesia	50	Mozambique	15
South Africa	10		

Source: Based on country reports (Eberhard (2015) and Lucarelli (2015)) and own assumptions.

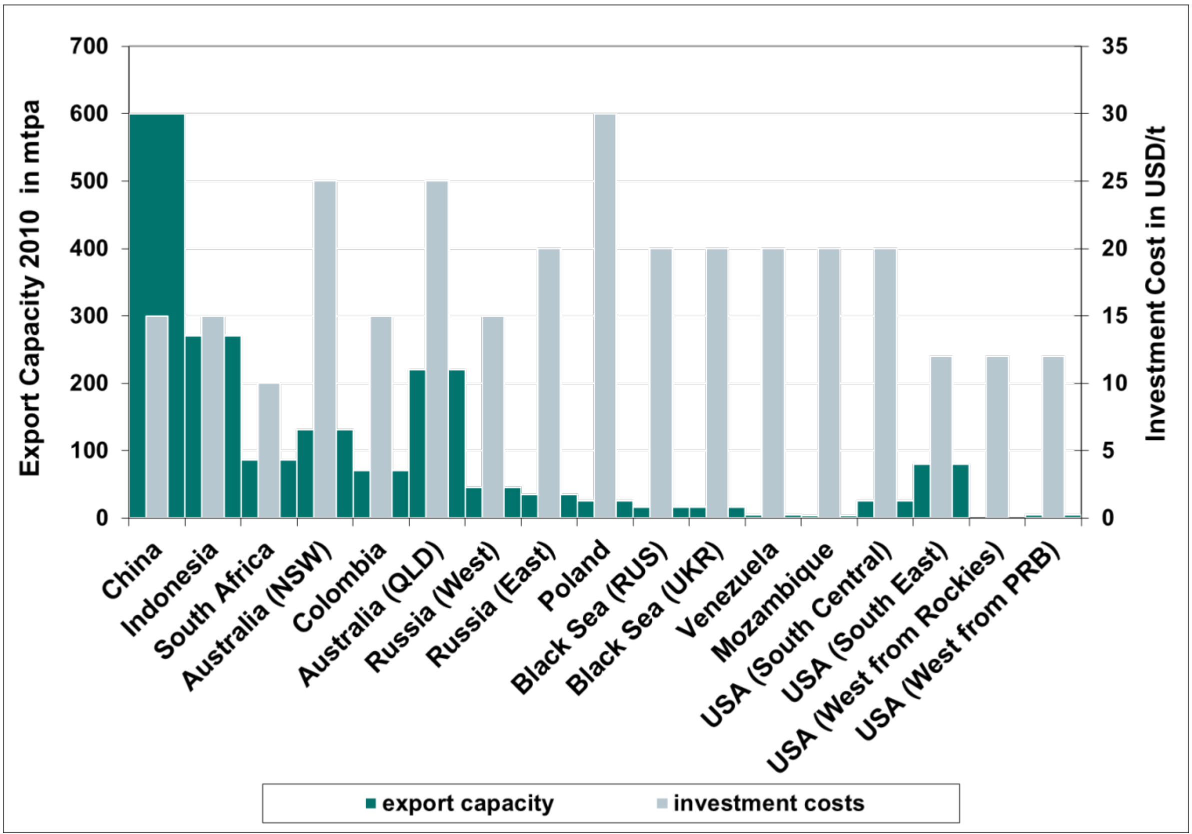


Figure 11: Capacity and investment costs for all export nodes in the base year.

Source: Authors' work based on IEA and OECD (2008) and Rademacher (2008).

China's politically determined export restriction is assigned to the Chinese exporter. For 2010 we use a value close to the actual exports of 20 Mt. 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: 2015: 80 Mt; 2020: 90 Mt; 2025: 100 Mt; 2030, 110 Mt; 2035: 120 Mt; 130 Mt from 2040 onwards.

In sum, the cost of a ton of exported coal is the sum of production costs, land transport costs and the export fee. This is shown in Figure 12 for each exporter. In this figure, we also include the range of production costs in the respective production region. This cost range is represented by a white bar in the figure; it is calculated by subtracting the lowest average costs (black bar) from the highest average costs of the production region. (Positive shadow values of binding constraints on production, transportation or export constraints may also increase effective costs in the model but they depend on the market outcome and are therefore not depicted here.)

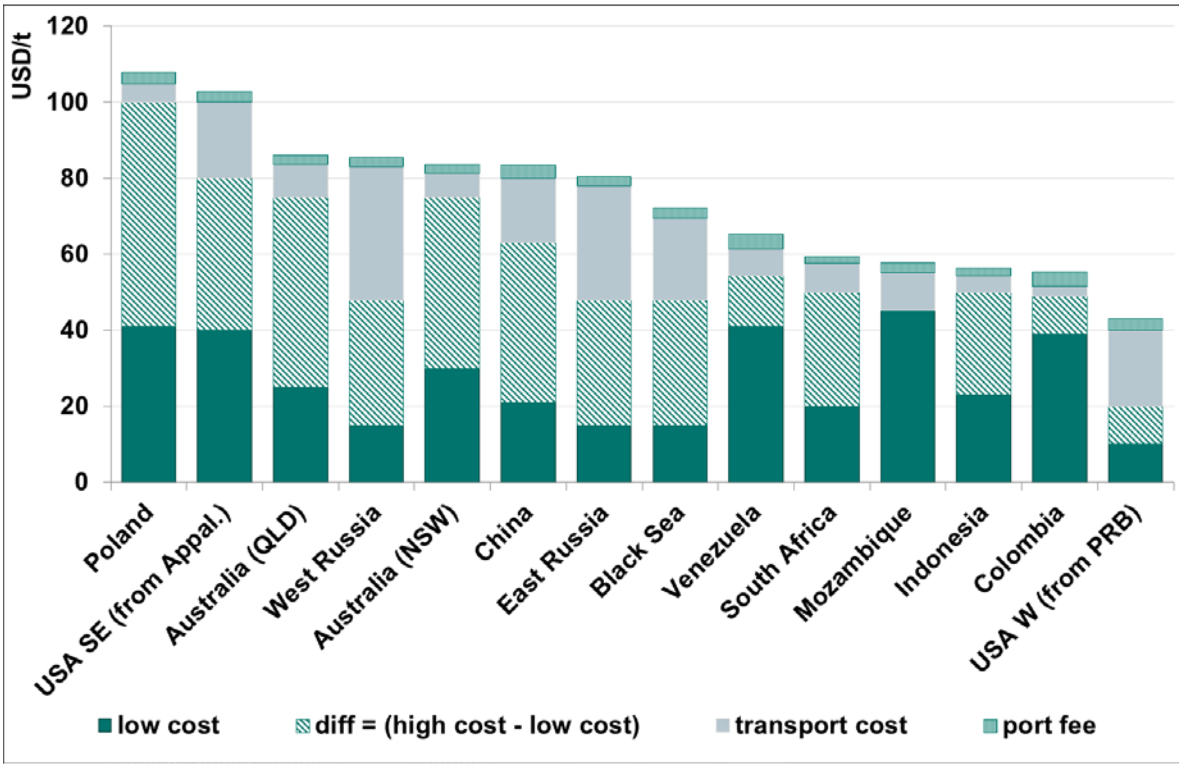


Figure 12: FOB costs (2010) for the export countries in COALMOD-World (in USD/t).

Source: Authors' work based on IEA (2012c); IEA (2011); Baruya (2007); NBSC (2007); and Ritschel and Schiffer (2007).

5.5 Freight rates

Overseas shipment is a cost to the coal importers that we approximate by the freight rates paid to the shipping companies. Freight rates result from the supply-demand equilibrium in the dry bulk carrier market and their quotations have been very volatile in the past.[13] In general, the freight market behaves cyclically. This makes it difficult to predict future freight rates, which are needed as a transportation cost input for the model. Moreover, for the same route there is 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

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

(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 the explanatory variable. This is necessary because freight rates are only reported for the major shipping routes and not for all exporter-importer pairs that we include in the model. We specify a different regression for 2010, which is based on 2010 observed data (obtained from Clarksons for all available coal shipping routes, including Panamax and Capesize), than for the subsequent model periods 2015–2040. For all future periods, we use data from 2002 to 2009 as input to the regression, to obtain long-run average costs.[14]

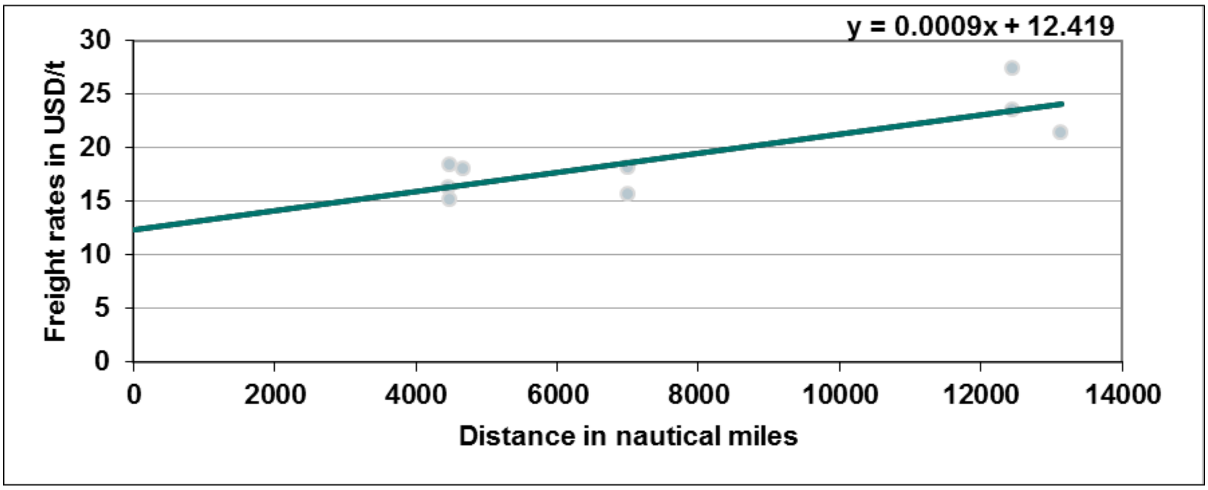


Figure 13: Linear regression of average freight rates between 2002 and 2009 (in USD/t).

Source: Authors' work based on Platts newsletters 2002–2009.

The regression equation for freight rate as a function of distance, determined using observed freight rate averages between 2002 and 2009 is y = 0.009x + 12.419. The computed values for y are used as shipping costs and are set constant from 2015 until 2040. The shipping costs between every export node and every import node with import possibility are calculated using this equation by plugging in the corresponding distance x.[15] Table 8 gives calculated freight rates for some main routes – for example, from South Africa (Richards Bay) to Northern Europe (Rotterdam). Freight rates on each route, in addition to export port fees, are added to the FOB costs depicted in Figure 12, which gives the CIF costs as shown in Figure 14. This figure does not include possible additional shadow values of restricted capacities (of production or export capacities) that may be computed in the model runs.

[14] Sources for weekly freight rates (end-of-week quotations) are Platts newsletters from 07/2002 to 10/2009 (where extreme values have been removed from the data).

[15] Distance is calculated using the PortWorld online distance calculator; see http://www.portworld.com/map/.

Table 8: Freight rates for selected routes (in USD/t).

From	Australia - Queensland	
To	2010	2015-2030
Rotterdam	20.47	23.72
Japan	14.97	15.69
From	Australia - New South Wales	
To	2010	2015-2030
Rotterdam	20.33	23.52
Korea	15.38	16.42
From	Colombia - Puerto Bolivar	
To	2010	2015-2030
Rotterdam	15.44	16.5
From	South Africa - Richards Bay	
To	2010	2015-2030
Rotterdam	16.94	18.65
Chennai	15.09	16.01
From	US West - Portland, OR	
To	2010	2015-2030
Rotterdam	18.08	20.29
Shanghai	15.72	16.91
From	Indonesia - Banjarmasin	
To	2010	2015-2030
Rotterdam	19.84	22.82
Guangzhou	13.76	14.09

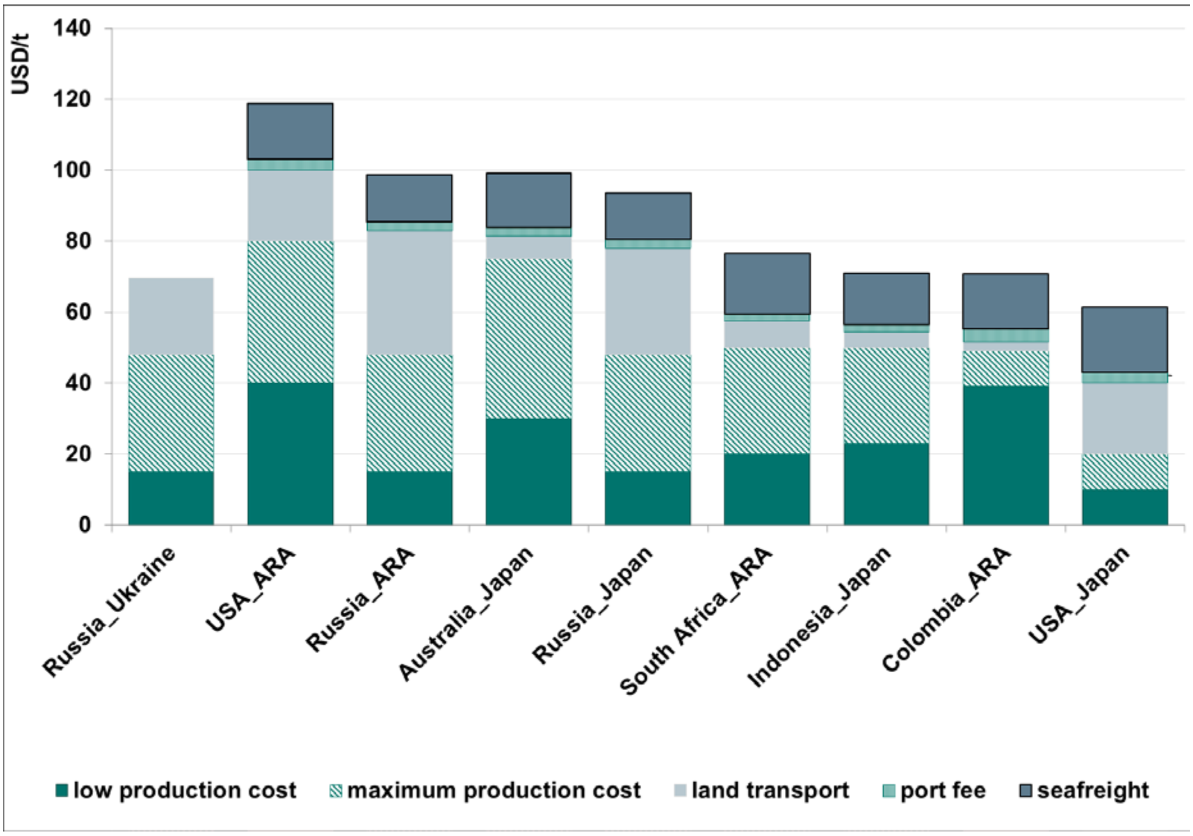


Figure 14: CIF costs in 2010 for selected routes (in USD/t).

5.6 Demand – Two possible scenarios

For the specification of the demand function of each consumption node, we need the "reference price" and "reference quantity" point for each model year. To obtain a consistent demand database for all countries in the model we use data from the International Energy Agency (IEA 2012a; IEA 2012b; IEA 2015a). IEA (2015a) reports on two scenarios which we use and contrast in the model: the New policies scenario in which coal demand continues to grow but at a much slower pace totaling in a 12% over the period 2013 to 2040; and the 450ppm scenario in which coal demand is significantly reduced almost to levels of 2000 (a reduction of 36% in the period from 2013 to 2040) due to some additional climate policy efforts.

The IEA (2012a; 2012b) reports demand data for 2010 of each consumer in Mtpa. This was converted to Petajoules using the calorific values for the main supplier from Table 6. IEA (2015a) gives coal demand projections until 2040 in the two scenarios. This is regionally aggregated data and steam coal is not distinguished from coking coal or lignite. Hence, for our demand scenarios we apply the regional growth rates between 2010 and each reported later period to the 2010 demand data obtained from IEA (2012a; 2012b) instead of using the reported consumption values directly. We generally use the growth rate of the reported coal consumption for power generation, except for China, India, and South American countries where we use the growth rate of the TPED (total primary energy demand) for coal.[16] This is due to the fact that China and India, but also Chile and Brazil currently still use a lot of steam coal in other consumption sectors (households, industry) and that, while we have to include this consumption, we need to take into account its falling tendency as reflected in the projected TPED growth rates.

Price data was taken from the IEA (2012a, CIF prices and steam coal prices for electricity generation). The prices in 2010 to 2050 in each scenario were calibrated such as to obtain the reference consumption in all demand nodes (with a margin of 1% or less) based on a cost-minimization approach for supply. The calibration resulted in an average price increase between 2010 and 2040 of 1.2% p.a. in the Stagnation scenario, which is derived from the New Policies scenario and reduction of 0.35% p.a. in the 2°C scenario, which is derived from the 450ppm scenario. These tendencies are in line with the trends projected by IEA (2015a).

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 of coal between -0.55 and -0.3. Aune et al. (2004) use a value of -0.19 for the short run elasticity of coal demand in their model. Liu (2004) yields a rather peculiar result of a zero elasticity that is 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 elasticity values 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

[16] In this, our approach is consistent with IEA (2015a, chapter "Coal Market Outlook").

its demand is assumed to be. We take into account a higher long-run elasticity of demand, which allows a structural change in the demand for coal depending on the expected future prices, by gradually increasing the price elasticities of each period over time: the values reached -0.4 in all countries by 2020, -0.5 by 2025, and -0.6 by 2030 and subsequent years.

Table 9: Reference consumption in 2020, 2030, 2040, by IEA region from New Policies and 450ppm Scenario, and extrapolation for 2050 (in % of 2013 consumption).[17]

	New Policies Scenario				450ppm Scenario				
Region [%]	2020	2030	2040	2050	2020	2030	2040	2050	Data origin
WORLD	103	107	112	112	95	74	64	45	TPED coal
OECD Americas	85	68	60	45	69	34	38	14	Coal in Electricity
USA	84	69	61	46	68	34	39	17	Coal in Electricity
OECD Europe	84	52	33	2	74	25	18	5	Coal in Electricity
European Union	82	46	27	4	73	25	19	5	Coal in Electricity
OECD Asia Oceania	90	79	65	53	84	38	16	4	Coal in Electricity
Japan	89	83	71	66	81	34	7	3	Coal in Electricity
E. Europe/Eurasia	93	87	87	84	84	44	29	5	Coal in Electricity
Russia	96	99	96	96	84	44	33	1	Coal in Electricity
Non OECD Asia	113	131	148	148	104	72	53	25	Coal in Electricity
China	100	101	96	96	96	75	61	42	TPED coal
India	140	202	274	274	130	135	133	133	TPED coal
Africa	111	127	152	152	88	81	66	56	Coal in Electricity
South Africa	99	95	89	84	96	75	59	40	TPED coal
Latin America	121	158	192	192	117	104	108	100	TPED coal
Brazil	125	144	163	163	119	100	94	81	TPED coal

Source: Own calculations based on IEA (2015a).

All consuming countries that are modeled as importers without domestic production are only included with their import demand by subtracting the respective local production from demand in the 2010 data. Where 2010 demand has to be allocated to several consumption nodes in one country, country-specific information is used.[18]

6 Modeling results until 2040

6.1 Scenario assumptions: stagnating coal demand or climate policies with significant demand reduction

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 and how strongly a specific constraint is binding. The results for the last two model years

[17] IEA (2015a) only covers the period until 2040, and only reports values for 2020, 2030, and 2040. Values for 2025 and 2035 where obtained by linear interpolation from the adjacent periods. Values for 2045 and 2050 were obtained by linear interpolation from value from 2020 to 2040. If the interpolation would have yield an increase we assumed constant demand from 2040 onwards, if the interpolation would have yield negative demand we assume a reduction of the 2040 by 50% for 2045 and by 75% by 2050.

[18] For the US, data from the EIA (2010, Spreadsheet Domestic Distribution of U.S. Coal by Origin State, Consumer, Destination and Method of Transportation) is used. For Russia, the allocation of demand is based on the regional location of coal-fired power plants given by EFA (2008). For China, the coal flows reported in Mou and Li (2012) are used to obtain the regional breakdown of demand. For India, Indiastat (2012, Spreadsheet Region/State-wise Linkage, Receipt, Import and Consumption of Coal in Various Thermal Power Stations) gives regional information.

2045 and 2050 are not presented as there is a risk of distortion because there is less incentive to invest without any possible revenue after 2050. For convenience, we only present the results for the years 2010, 2020, 2030, and 2040 here.

Our results are based on the assumption of competitive and liberalized markets.[19] 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. We assume that no fundamental structural change in the coal market will happen during the model horizon. The model 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. We further assume that there are no policy-based restrictions on trade apart from the case of Chinese exports in 2010.

We examine two scenarios: the “Stagnation scenario”, which is derived from the IEA’s World Energy Outlook’s New Policies scenario, and the “2°C scenario”, which is derived from the IEA’s World Energy Outlook’s 450ppm scenario (IEA 2015a).

The two scenarios fundamentally differ in the energy mix induced by climate policy efforts and, hence, in CO_2 emissions. Globally and from all sectors, annual energy-related CO_2 emissions increase by 16% in the New Policies Scenario between 2013 and 2040. By contrast, in the 450ppm scenario global emissions are reduced by 41%. The relative contribution of coal to total CO_2 emissions by 2040 is forecast to be slightly reduced from 46% to 42% in the New Policies scenario and but substantially decrease to 24% in the 450ppm scenario.[20] In other words, at the global scale, a structural transformation involving a drastic shift away from coal is expected in the second scenario.

Regional consumption patterns are affected in the two scenarios by the instruments and relative stringency of climate policy across regions. The IEA scenarios assume the implementation of the 2030 Climate and Energy Package for the EU, a phase-out of fossil fuel subsidies for all Non-OECD countries where such policies were already announced, the implementation of various policies directed at reducing fossil fuel consumption and improving air quality, and also some mitigation efforts in India. To achieve stringent emission targets in the 450ppm scenario the storyline assumes introduction of CO_2-pricing regime by 2020 for all OECD and major Non-OECD countries, and a comprehensive phase-out of fossil fuel subsidies in Non-OECD countries.

We incorporate these national differences in the scenario assumptions in COALMOD-World by using the coal consumption projections from the respective IEA scenarios. Specifically, we use the demand growth projections for coal for power generation in the respective scenarios, with the exception of

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[19] We are aware that not all countries currently have fully liberalized domestic markets, e.g., India. However, we assume that the markets’ structure or outcomes will move toward competitiveness in the future.

[20] CCTS plays at best a marginal role in reducing CO_2 emissions from coal consumption in the New Policies scenario with 3% of the coal-fired generation fleet being equipped with Carbon Capture technology. By contrast, the 450ppm scenario relies heavily on CCTS with a penetration of 75% by 2040. We take a critical view on the CCTS technology assuming that even strong climate change mitigation efforts will not lead to a significant deployment (see Hirschhausen et al. (2012). Therefore, we interpret the coal demand patterns implied by the 450ppm scenario as an upper bound, with even stronger reductions of coal consumption necessary in the absence of CCTS.

China and India, South Africa, and Latin American countries where the growth rates of Total Primary Energy Demand (TPED) from coal are used (for more details, see section 5.6 and, in the Appendix). This gives the global steam coal demand for each scenario as shown in Figure 15.

We assume that there are restrictions on export capacity expansion for 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 that can be added over a five-year period depending on the country. We include export restriction for US coal via west coast ports in line with the current lack of such domestic capacity (minor amounts are exported via British Colombia) and persistent concerns about environmental and health impacts (Western Interstate Energy Board 2015). We do not impose restrictions on expansions of inland transport capacity due to a lack of detailed data on this for all modeled countries.

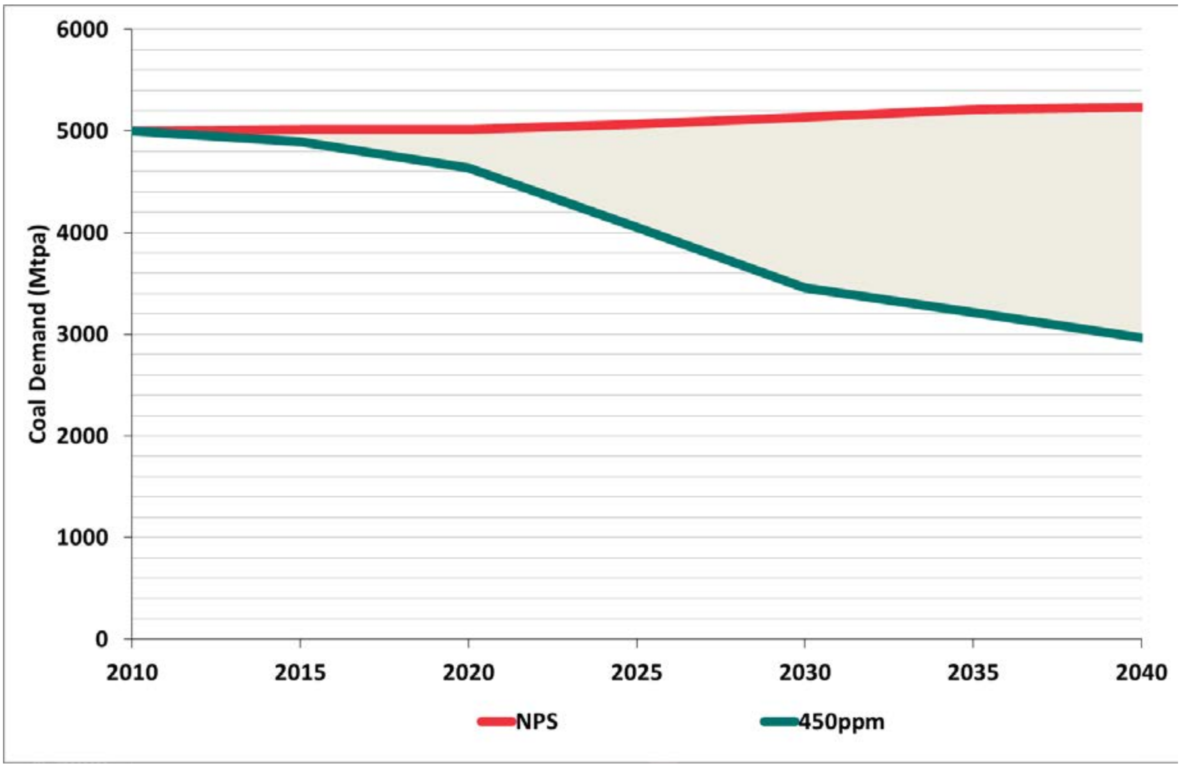

Figure 15: COALMOD-World results: development of yearly global coal demand in both scenarios until 2040 (in Mtpa).[21]

6.2 Overview of results: stifled Asian “hunger” for coal

Figure 16 and Figure 17 give an overview of the evolution of consumption in the world steam coal market in our Stagnation scenario and 2°C scenario and provide more detail on the supply structure. The total surface of this graph represents total consumption, and the different areas decompose the

[21] COALMOD-World is an energy-based model that calculates trade flows in Petajoules. For better representation, the results shown are aggregated and expressed in Mtpa. These values are calculated using the relevant quality factors of each producer. Detailed results are reported in Table A.4 in the Appendix.

consumption by its origin, seaborne trade or local domestic supply with a special focus on India and China. In the Stagnation scenario, global coal consumption will remain more or less constant with a moderate increase of 5% from 5000 Mtpa in 2010 to 5235 Mtpa in 2040. Most increase in demand originates from rising consumption in India. Rising demand in South-East Asian countries is overridden by decrease in demand from OECD countries.

In contrast, the 2°C scenario sees a decrease in steam coal consumption by more than 40% to 2091 Mtpa in 2040. All countries drastically reduce their demand with a steeper decease between 2020 and 2030 and a less steep reduction before and after. The stark exception is India, where consumption increases by 29% until 2040. This corresponds to an average emissions reduction of 3.6 $GtCO_2$/a over the model horizon.

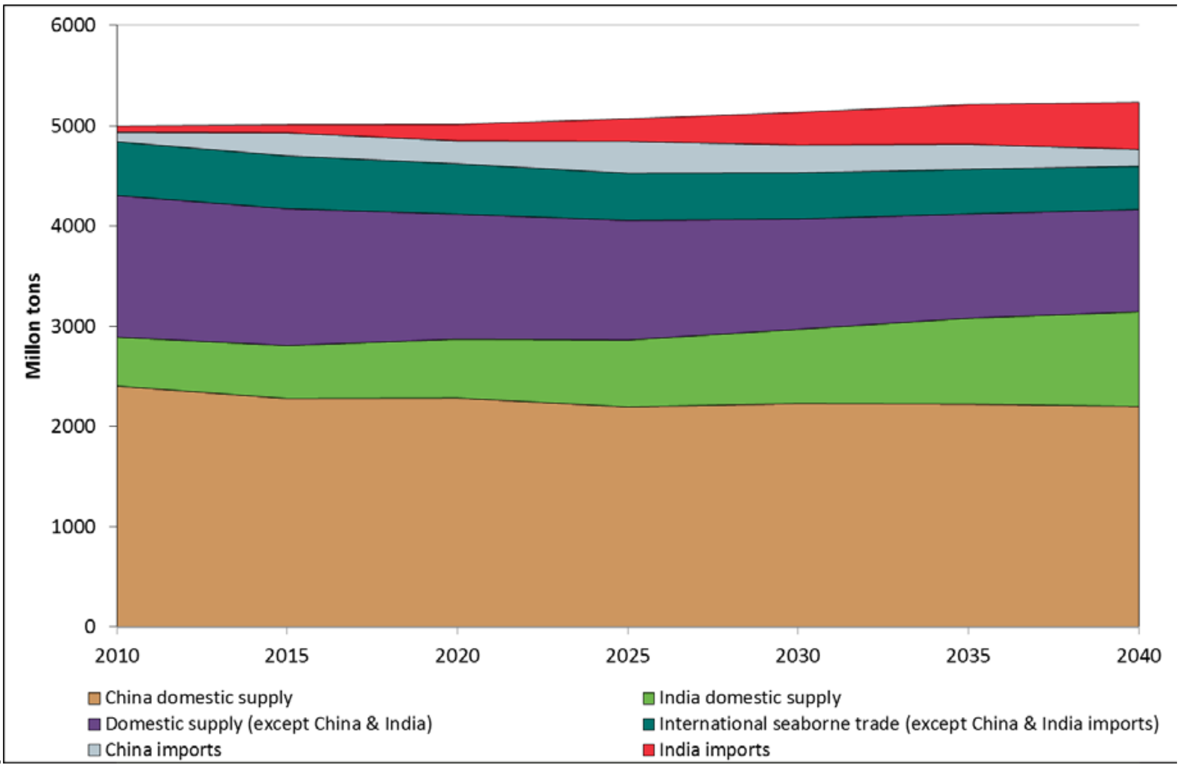

Figure 16: Global COALMOD-World results: aggregated consumption and imports in the Stagnation scenario (in Mtpa).

Some similar trends can be observed in both scenarios. Around 20% of coal consumed is imported traded on the seaborne market in 2040, up from about 15% in 2010. In both scenarios, the largest share of consumption takes place in Asia, in particular in China and India. Asia[22] accounts for about 68% of global consumption in 2010, this share increases to 79% until for both scenarios, with China alone consuming about 45% (Stagnation scenario) to 51% of the global coal supplies by 2040.

As China's import behavior is rather driven by arbitrage than by structural supply restrictions (e.g., Morse and He 2015), it is not surprising that the share of imports in total consumption is higher in the 2°C scenario (19% as compared to 7% in the Stagnation scenario). Chinese coastal consumers

[22] Without Israel, Turkey, Central Asia and Russia, and Oceania.

benefit from lower market prices which originate from overall lower demand. In general, India relies more heavily on imported steam coal with its share rising from 11% in 2010 to 33% in 2040 for the Stagnation scenario and more moderate 24% in the 2°C scenario. In absolute terms this corresponds to a 770% increase from 2010 to 2040 for the former and a 282% increase for the latter scenario. In 2010, the two countries account for 23% of seaborne trade. Already by 2025, their imports account from more than half of seaborne trade. This share rises to 60% and 75% until 2040 for the Stagnation scenario and the 2°C scenario, respectively.

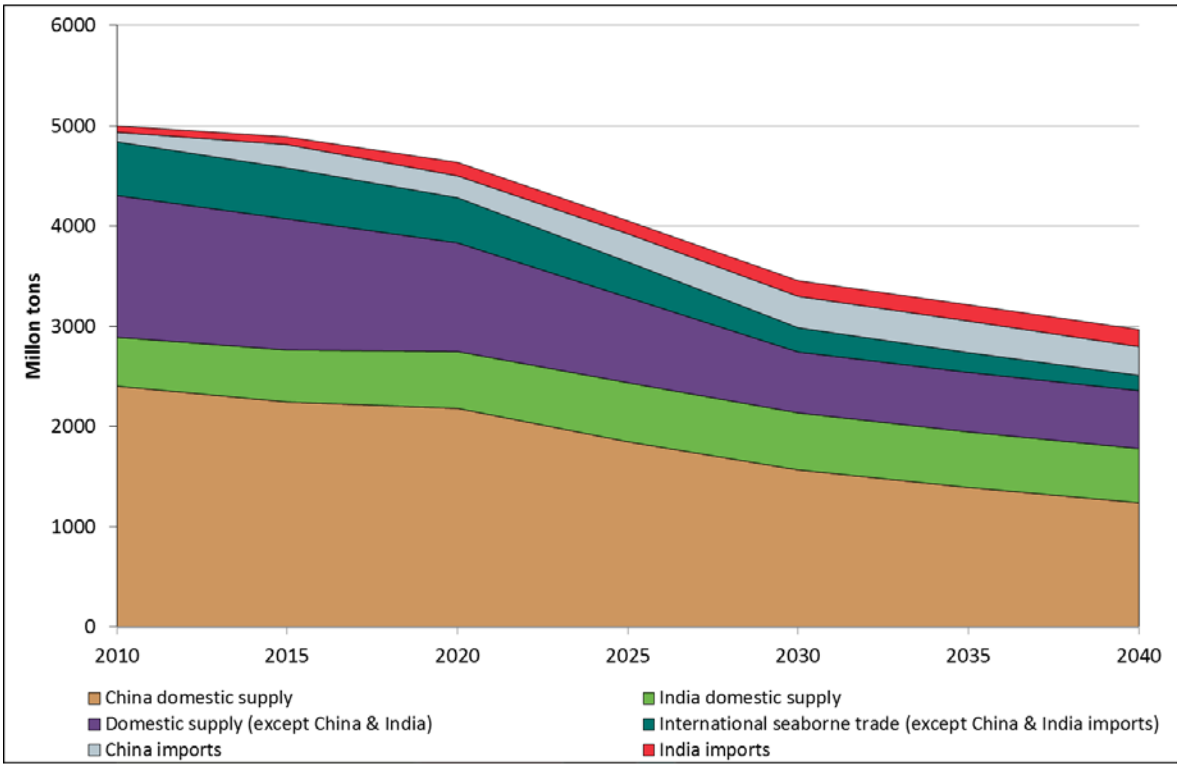

Figure 17: Global COALMOD-World results: aggregated consumption and imports in the 2°C scenario (in Mtpa).

Table 9 shows that, in addition to the big players China and India, other Asian countries also increase their coal demand to a varying extent in the two scenarios. Indonesia, to date mostly known as one of the largest exporters, is expected to see a moderate growth of domestic coal consumption – a development which may also influence its exporting behavior if new mining areas are too costly to be added to the reserve base. Moreover, other South-East Asian importers –Taiwan, Thailand, Malaysia, and the Philippines – will increase their demand in the Stagnation scenario. Besides, Latin American consumers like Chile, Mexico and Brazil are also expected to increase consumption.

6.3 Global trade results

6.3.1 A shift to Asia

The major focus of the modeling effort is on investigating international trade flows. We obtain long run equilibrium results which abstract from the volatility of prices or costs, which may cause coal trade flows to diverge from real-world observations in the short run. Our modeling approach implicitly assumes that the production and investment quantities as well as the trade flows of the equilibrium path will be reflective of long-run trends.

The results for 2010 show a notable similarity with the actual observed trade pattern. This is an important achievement, given that we not only simulate the trade flows shown on the maps in Figure 18 to Figure 21 but also internal markets. We have a global integrated market with flows from South Africa and North America, traditional suppliers of the Atlantic basin, to Asia in the Pacific basin. The direction and relative amounts of the trade flows are a reasonable match to actual trade flows.

Figure 19 and Figure 21 show the trade flows in 2020 and 2040 in a stylized and simplified representation, distinguishing Stagnation scenario and 2°C scenario results. Most obviously, the demand reduction in Europe and North America and the consumption increase in Asia lead to a noticeable shift of international trade flows to Asia. This is the case not only in the Stagnation scenario but also in the 2°C scenario. This is due to the concentration of climate and energy efficiency policies in Europe and North America, as well as China and OECD Asia, while South-East Asia and India pursue a carbon-intensive development path. The model predicts that the overall picture for the global market will have significantly changed by 2040: Russia and Poland are the only suppliers to Europe; South Africa, Europe's traditional supplier, will have become a major supplier to India and the Pacific market; and Colombia also mainly delivers to the Pacific market.

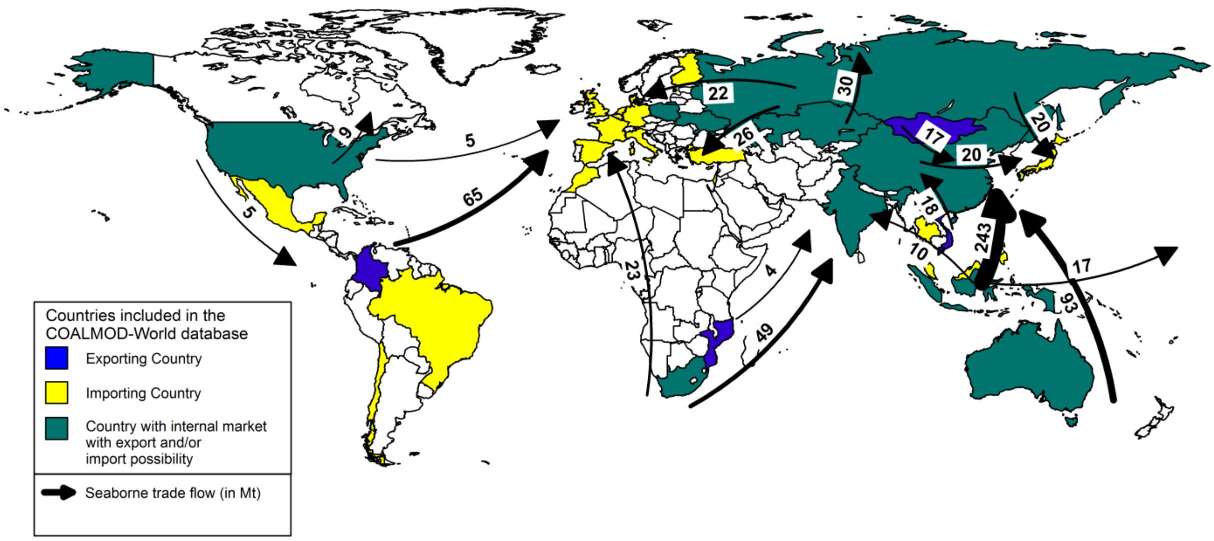

Figure 18: Global results 2010: seaborne trade flows (in Mtpa).

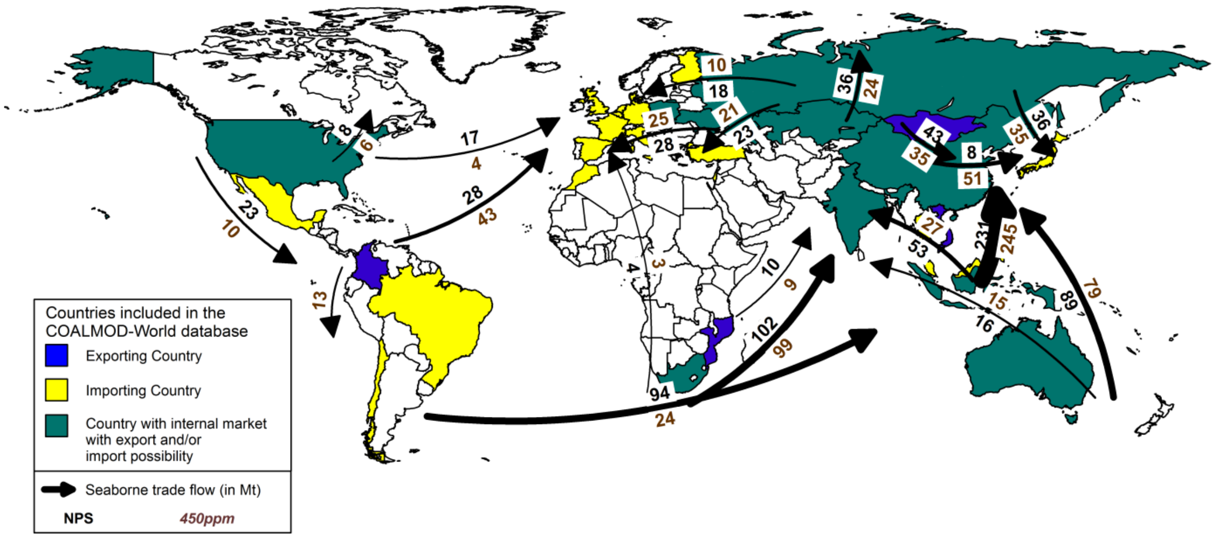

Figure 19: Global results 2020: seaborne trade flows in both scenarios (in Mtpa).

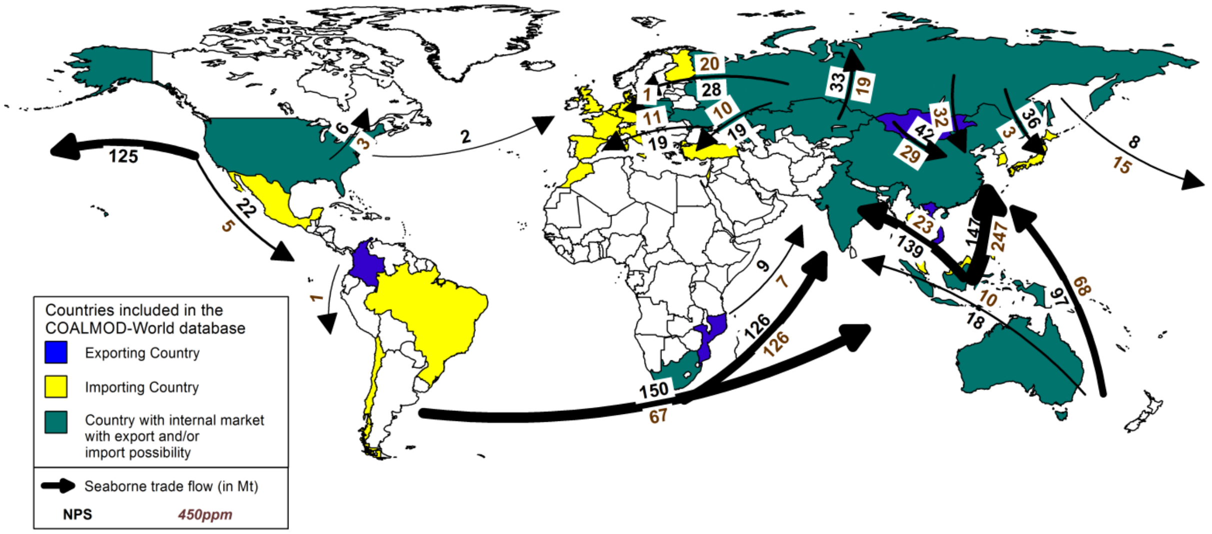

Figure 20: Global results 2030: seaborne trade flows in both scenarios (in Mtpa).

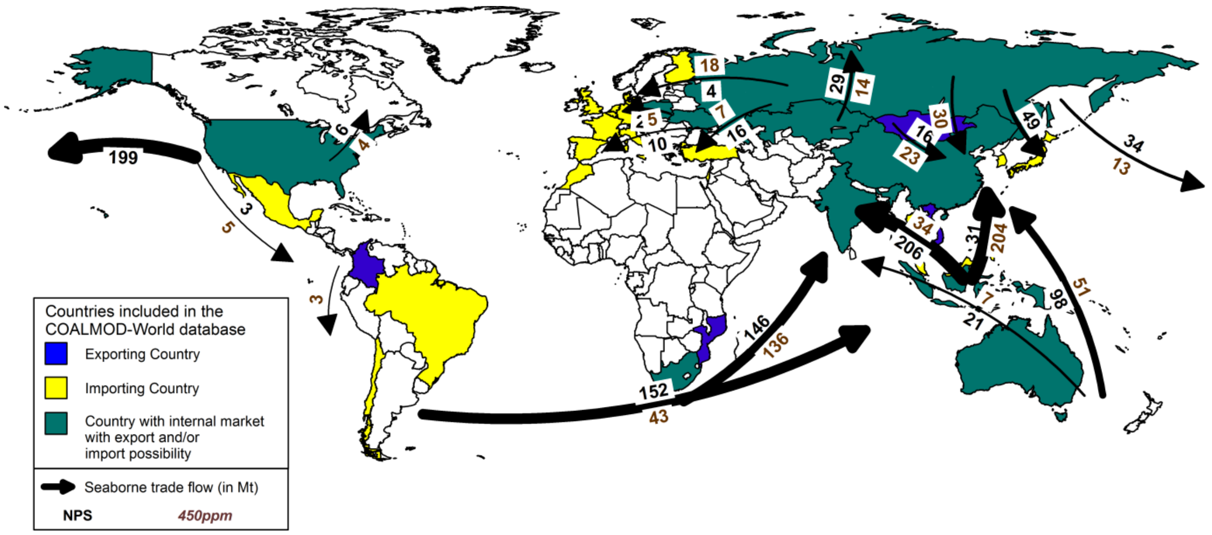

Figure 21: Global results 2040: seaborne trade flows in both scenarios (in Mtpa).

In some circumstances the US will join the group of large exporters. Challenged by a decline in consumption due to the availability of cheap shale gas, and by strict environmental and climate regulation (most notably the Clean Power Plan) the US coal industry is in crisis with major bankruptcies in 2015 and 2016 (EIA 2015).[26] Sustaining the trend, coal from Powder River Basin (PRB) in Wyoming and Montana can extend its dominate role on the US domestic market, due to its cost advantage and abundance. Given that there will be no climate policies addressing leakage from US domestic coal markets to international markets, the latter may be an outlet to the stranded coal if international prices recover. In our model high cost US suppliers increasingly export coal to Asian, and to a smaller extent to Latin American markets. Until 2040, the US becomes the second largest supply to international markets, up from the 8th rank in 2010.

The third most important exporter in 2010 was South Africa. Given further increase of its exports after an expansion of its critical railway capacities to the ports, South Africa is predicted to retain its ranking. After years as swing supplies between Europe and Asia, we expect South African exports quickly to be redirected to Asia alone, and especially to India. We can see the emergence of a third market (in addition to the traditional Atlantic and Pacific markets) that could be called the “Indian market”, where South Africa will become the key player. However, the depletion of current operating mines and lower quality and long transport distances for new mines might reduce South Africa’s ability to dominate this market, especial if India’s plans to shift to modern coal-fired power plants which required high quality coal are realized (Eberhard 2015; Commonwealth of Australia 2015).

Table 10: Share and rank in international trade flows of major exporters in both scenarios and over time.

	Stagnation scenario								2°C scenario					
	Share of international trade [%]				Rank in international trade				Share of international trade [%]			Rank in international trade		
	2010	2020	2030	2040	2010	2020	2030	2040	2020	2030	2040	2020	2030	2040
AUS	13	12	11	11	2	4	5	5	12	11	10	3	3	4
COL	9	12	13	13	5	2	3	4	9	8	7	5	5	5
IDN	39	32	27	22	1	1	1	1	34	38	39	1	1	1
MNG	2	5	4	1	10	7	7	10	4	4	4	7	6	6
RUS	10	11	10	10	4	5	6	6	11	11	11	4	4	3
USA	3	5	15	19	8	6	2	2	3	1	1	10	9	9
ZAF	10	12	12	14	3	3	4	3	13	18	22	2	2	2

6.3.2 Other trends

Colombia, and with a similar pattern the smaller Latin American exporter Venezuela, has traditionally been a supplier to the Atlantic basin. In 2010, Europe was its main export destination. However, through the extension of the Panama Canal, these suppliers now also have easier access to the Asian

[26] Mooney and Mufson (2016): “How Coal Titan Peabody, the World’s Largest, Fell into Bankruptcy.” *The Washington Post*, April 13. https://www.washingtonpost.com/news/energy-environment/wp/2016/04/13/coal-titan-peabody-energy-files-for-bankruptcy/ [accessed 23.07.2016, 15:41].

market. [27] Due to low demand and low prices, there is a major swing to the Asian markets until 2020, and a full reorientation until 2030, according to the simulation. Colombia has repeatedly faced infrastructure bottlenecks in the past (e.g., in its railroad transportation). If these are resolved, Colombia can considerably increase its market share thanks to its relatively low production costs.

Russia strengthens its position as an important supplier in the European market, taking over market shares from South Africa and Colombia, which turn more to the Asian market. By 2030, approximately 86% of European steam coal demand is served by Russia in both scenarios. Against the background of concerns about security of supply from Russia this might not be a favorable development for European consumers. While the model forecasts a price differential of about 8% between Europe and prices paid in India and China, this gap might be smaller if the Europeans opt for a self-imposed diversification of suppliers. In both scenarios, Russia is also increasingly active on the Asian market with supplies to Japan, Korea and China. To a smaller extent it is also active on the Latin American market.

In the model scenarios, China will cease its exports to other countries due to its strong domestic demand, and diminishing cost advantages compared to Indonesian suppliers. Hence, the export restriction, which was still binding in the last decade, will play no role any more. China increases its import levels in the next decades on different paths in the two scenarios: in the Stagnation scenario, imports gradually increase from just under 100 Mtpa in 2010 to 278 Mtpa in 2030; and to 313 Mtpa in the 2°C scenario. In both scenarios there is a drop after 2030, which is more pronounced in the Stagnation scenario (down to 168 Mtpa) and less pronounced in the 2°C scenario (down to 286 Mtpa). The divergence is driven by lower global demand which results in increased availability of low-cost coal on the international market.

Interestingly, China also will rely on coal supplies from Mongolia in addition to imports from the seaborne market that can land in the demand regions along the coast. Mongolia has recently started to scale up its coal production and will continue to do so according to the model by relying on the stable market for its coal in China.

The supply relations in Asia also explain the expansions of export capacities of the major suppliers and their sensitivity to demand changes. Table 11 reports the difference of export capacity expansions in 2°C scenario compared to the Stagnation scenario for some major exporters. As could be expected from the assumption of policies that curtail coal demand after 2020 in all countries except India, there is no need for export capacity expansions for any of the established international suppliers. It is only the new entrants like Venezuela and Mozambique who expand their capacity after 2020. The exception is South Africa, which consolidates its position on the "Indian market", and substantially expands its export capacity, though still by less than in the Stagnation Scenario.

[27] Wallis (2016): "Expanded Panama Canal: Bigger Ships, Bigger Paydays for Beans, Coal, Gas." Reuters. June 25. http://www.reuters.com/article/us-panama-canal-commodities-idUSKCN0ZB0Z0. [accessed 24.07.2016, 20:57]

Table 11: Export capacity and production capacity: results of 2°C scenario compared to Stagnation scenario (in Mtpa).

Export country	2020	2030	2040	Producer country	2020	2030	2040
AUS	0	0	0	AUS	0	0	-7
COL	-42	-66	-69	CHN	-20	-324	-362
IDN	-12	-20	-20	COL	-42	-77	-96
MOZ	-1	-1	-1	IDN	-18	-49	-46
RUS	-11	-15	-17	IND	-15	-162	-349
UKR	-5	-5	-5	MNG	-8	-13	-11
USA	-35	-75	-127	RUS	0	-2	-14
VEN	0	-4	-4	USA	-59	-91	-94
ZAF	0	0	-10	ZAF	-10	-33	-54

The reduced demand in the 2°C scenario is, of course, reflected in slower production growth. Less new production capacity has to be built to accommodate the lower consumption levels, as reported in Table 11, which shows the difference between production capacity expansions in the 2°C scenario compared to the Stagnation scenario.[28] Most notably, the US and Colombia, and to a smaller extend South Africa, exhibit significantly reduced export-oriented production capacities in the 2°C scenario.

6.4 Price analysis

COALMOD-World calculates prices in each demand region. The price is the fundamental signal that attracts coal into a market and reflects that market's willingness to pay. In our perfect competition setup, the price equals the production and transportation costs of the highest cost supplier (the so-called marginal supplier, i.e., the supplier of the last, marginal unit) plus any possible shadow prices of the various constraints. Hence, prices may vary significantly between regions depending on the willingness to pay (demand function) and the availability of high-cost and low-cost suppliers. Regional (nodal) prices are calculated in the model calibration mechanism so as to obtain the consumption levels set by the reference data. In other words, the price results show what price level is necessary to reach a given consumption level. Our model cannot predict short-term price volatility but gives long-term price trends based on the fundamentals of the market.[29]

Figure 22 shows the price evolution for some major regions in the Stagnation scenario. Globally, prices show an upward trend over the time period 2010 to 2040. We observe continuous price increases of 1.22% p.a. on average in the Stagnation scenario and a reduction 0.4 % p.a. in the 2°C scenario until 2040 – that is, an increase of 37% or a decrease of 10%, respectively, over the time horizon.

[28] Note that this table reports on the levels of production capacities and does include absent investments in new mines that replace old mining capacities in line with the mining mortality mechanism.

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

The lowest prices are the domestic prices in the US, South Africa, and Russia. These demand nodes are close to large and cheap sources of supply and are not connected by imports to the global market; thus, they are less affected by higher prices in other regions. While the latter two still show some moderate increase over time, domestic US prices decrease from 54 USD/t to 52 USD/t, with a low of 49 USD/t in 2020. This is in line with the observation of reduced demand, couple with overcapacity and cheap supply from Powder River Basin.

In the near term, highest prices are the import prices in Europe, the Mediterranean countries and in particular in China due to the long transport distances (with high transport costs) and the high willingness to pay. The second highest increase over time can be seen in the South-East Asian prices. This is due a rising demand that is met by supply where the marginal supplier (often Australia) has faces increasing production costs. The highest increase, however, can be observed with Indian import, and even more so with Indian domestic prices. With no access to the international markets and a strong demand cost of supply and therefore also prices increase more than double from 2010 to 2040. Two opposing effects govern the trend of European prices. On the one hand low cost suppliers increasingly turn to Asia to ear there margins, therefore consumers have to rely on high cost supply from Russia and Poland. On the other hand, when demand is drastically reduced especially in 2030 and onwards, prices decrease again.

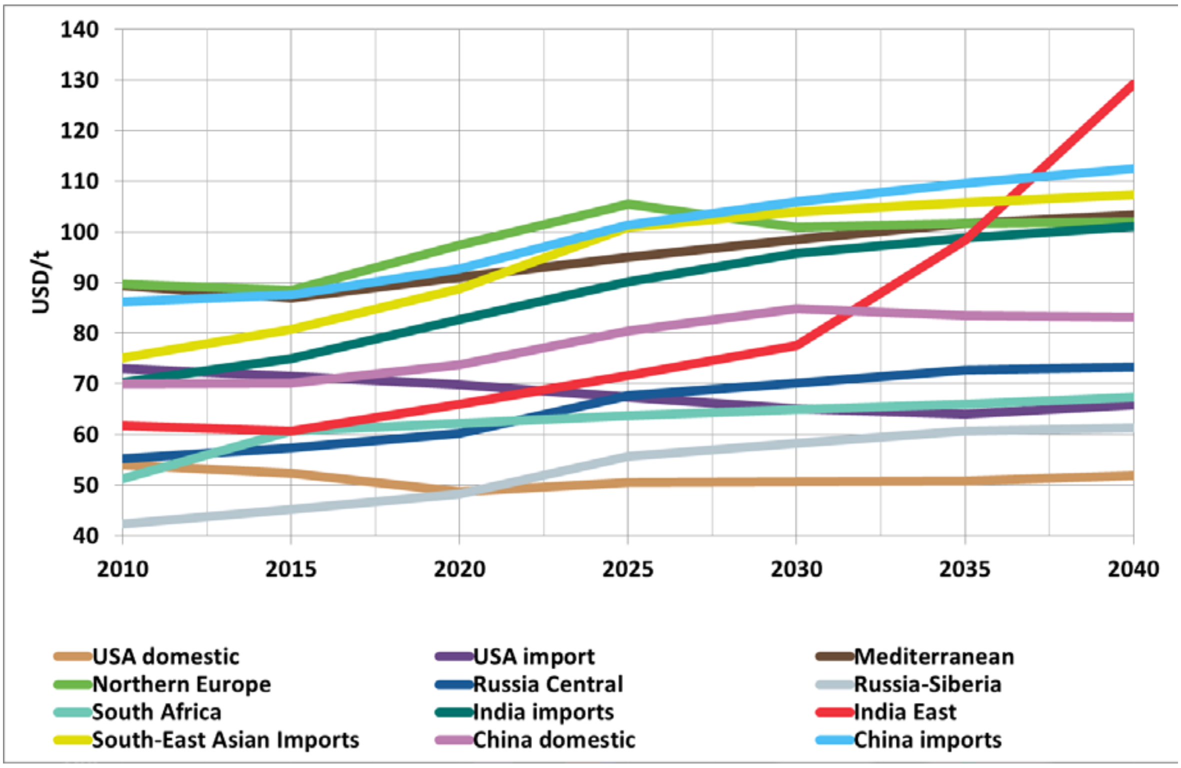

Figure 22: Average prices for selected regions for all model years (in USD/t) in the Stagnation scenario.

It is noteworthy to look at the development of production costs in Figure 23 and Figure 24 since the prices reflect the costs along the value chain of the marginal supplier in the perfectly competitive market (in addition to shadow values of binding capacity constraints). The production cost function changes over time (i.e., shifts upward) due to the mine mortality mechanism in the model, which leads to an upward movement of the cost curve's intercept. The upward trend is more or less fast for each producer, depending the respective mine mortality, but also on additional production capacity expansion. For example it is considerably slower for the Powder River Basin than for Colombia or Australia. The decisive point of the cost curve is the cost level of the last produced unit; this is what is depicted in its development over time in Figure 23 and Figure 24 (compare to the 2010 cost curves in in section 5.2).

Both figures confirm the picture of the base year (2010) cost order for the following years: Australia, and the US Appalachian are the most expensive producer, followed by China SIS. South Africa, Colombia, and Indonesia are in the group of medium cost suppliers, undermined by Russian coal, which faces long-distance haulage, though. The US Powder River Basin is the cheapest supplier on the world market. The grouping remains more or less unchanged throughout the model horizon, with the exception of Colombia who's production costs rises faster than those of South African and Indonesian competitors.

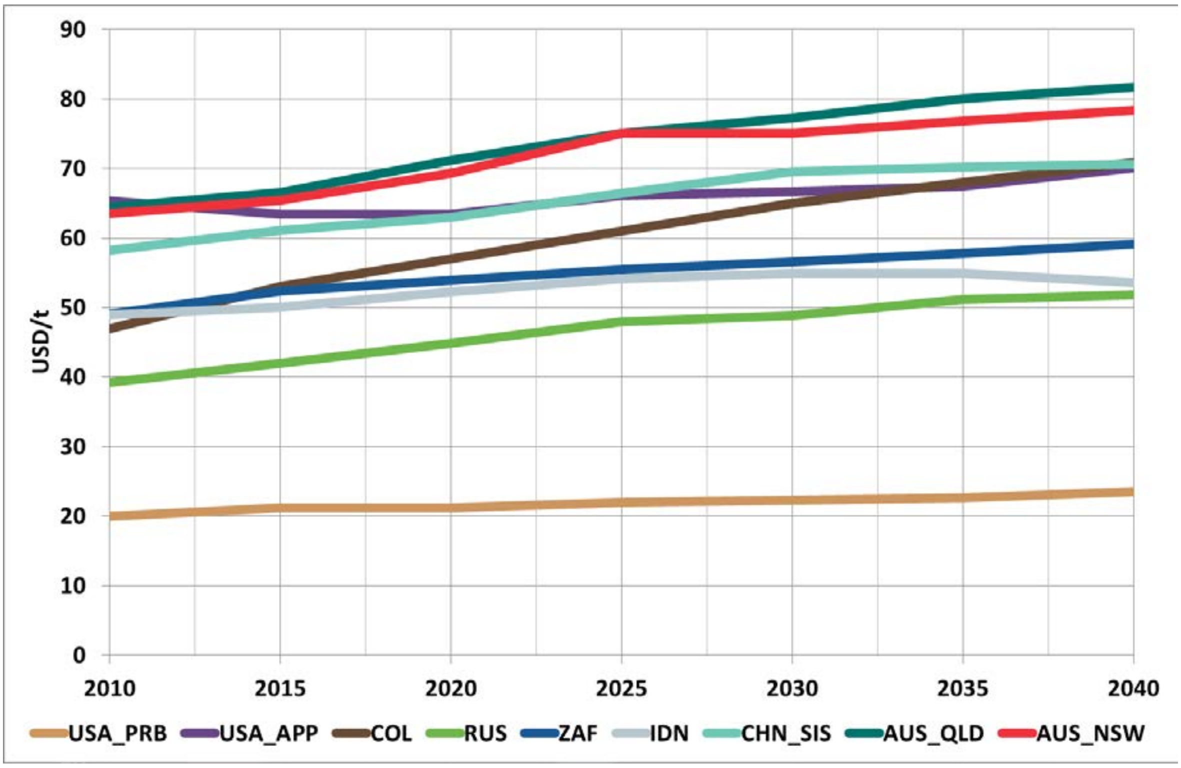

Figure 23: Production costs at production level for selected producers over time in the Stagnation Scenario.

The lower consumption levels of steam coal in the 2°C scenario lead to a lower cost (and price) level than in the Stagnation scenario. The decrease in production cost which can be observed in Figure 24 originates from a decrease in production levels. Most pronounced cost reductions can be observed for the Appalachian region, Australian and Chinese producers. While highest costs are found at 82 USD/t in Queensland, Australia in 2040 in the Stagnation scenario, costs are down to 56 USD/t in the same region in the 2°C scenario.

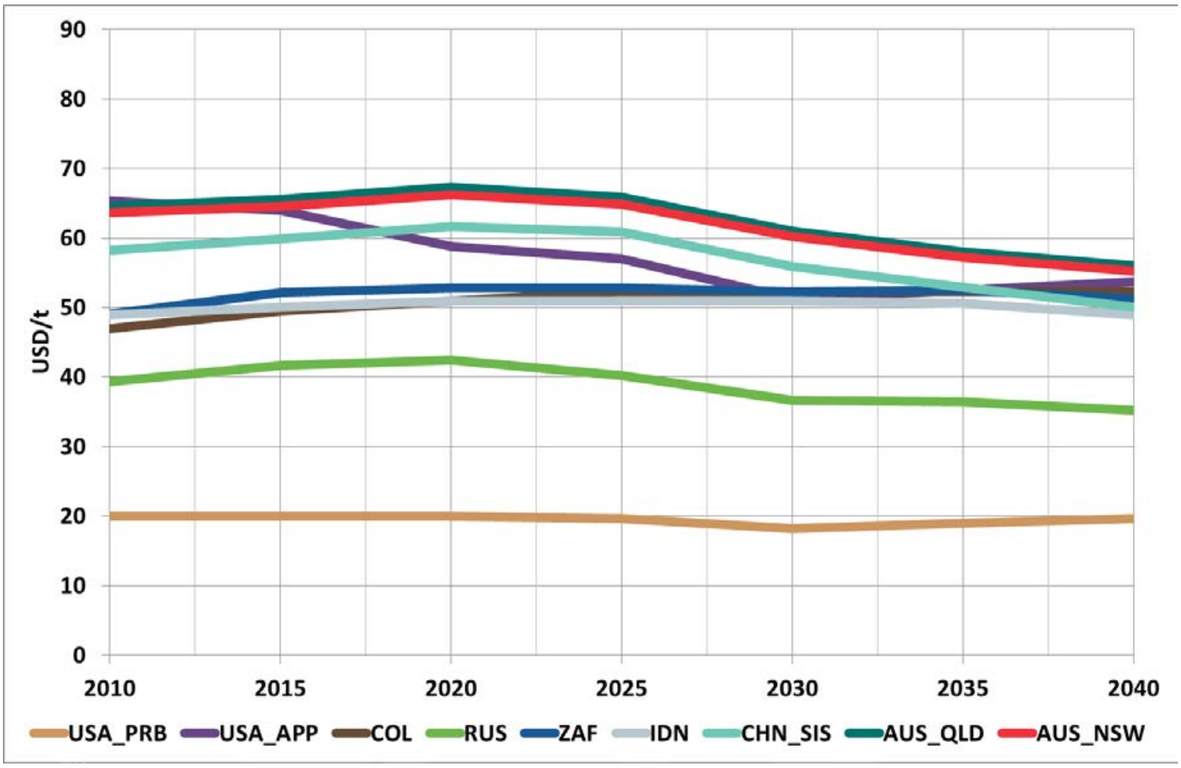

Figure 24: Production costs at production level for selected producers over time in the Moderate Growth scenario.

7 Model Limitations

While COALMOD-World constitutes a data-rich and comprehensive modeling framework that can be applied for various types of analysis, the model still has some inherent limitations that are briefly discussed in this section.

In the model demand response and induced changes in supply patterns are driven by price elasticities. The framework assumes an inverse demand function which is estimated based on reference demand, reference prices, and some ideal about the point elasticity. In contrast to a General Equilibrium framework, the commodity that is used to substitute reduced demand in coal is not specified. Therefore, calculated emission reductions for any policy scenario must be considered as upper bounds, as the substitution may also be towards other fossil fuels, e.g., natural gas rather than to zero emission renewable energy sources.

Moreover, the model does not take into account macro-economic parameters and Interaction of coal prices with other key commodity prices, most notably the oil price, as a major input to production costs as fuel for machinery and transport. Exchange rates, which are commonly adjusted by exporting countries to mitigate price fluctuations, are also not considered. Such interactions, just like industry business cycle effects, have strong short-term implications on coal prices. As COALMOD-World is more concerned with the medium to long-term development of the steam coal market, the model abstracts from such short-term adjustments. For the analysis of supply and demand-side disruptions or market power exertion such additional determinates would highly increase the accuracy of results.

It is also worth noting that coal quality in terms of gross calorific value is an important characteristic of coal that determines the value of the commodity but also its substitutability. Often, power plants are tailored to a particular type of coal that is required for the combustion process and deviations induce additional costs due to reduction in efficiency and additional maintenance. The model does not account for this fact, and assumes that all steam coals are perfect substitutes based on their energy content. Moreover, the model assumes that quality of coal for a particular producer is constant over time. In reality, the quality of coal produced from a mine can vary substantially over time depending on geological characteristics of the current coal seam. Haftendorn, Holz, and Hirschhausen (2012) propose a formulation of COALMOD-World that accounts of changing quality over time. Due to a lack of data for parametrization the formulation presented in this report does not include this feature.

Finally, the model focuses on steam coal which is relevant for the international market. There are interrelations and some substitution between other types of coal, i.e. lignite and coking coal. There is a fluent passage between lignite and steam coal and also between steam coal and coking coal, where the latter are often mined in the same mines. Policies directed towards the one commodity might well have effect on the other. A comprehensive approach covering all types of coal and their particular use would deliver a more holistic picture but is difficult to accomplish due to the heterogeneity of cases.

8 Conclusions

In this report, we have presented a tool for examining the future global steam coal market, the COALMOD-World model. We have shown how we can model this market and its future development 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 illustrative results are based on two IEA World Energy Outlook scenarios (IEA 2015a): The market equilibria obtained from demand projections based on the “New Policies Scenario”, which includes some minor implementation of climate policy resulting in a stagnation of coal demand, and the “2°C scenario” which induces a coal demand path consistent with the 2°C target and is derived from the IEA 450ppm scenario.

While both scenarios share the general trend of a shift of the international steam coal market towards Asia, they imply two fundamentally different development paths for the steam coal market. Demanded quantities differ by over 46% in 2040 and observed prices vary between an almost 40% increase and a 10% decrease. Internationally traded volumes diverge by almost 500 Mtpa in 2040 with different trade relations, and required investments in production, transport and export capacity implied by the two scenarios.

The comparison demonstrates the functionalities of the model and provides examples for possible insights gained from the modeling exercise. At the same time, the discussion also illustrates that the model results can only be interpreted in the context of a specific market situation and political context, in combination with idiosyncratic expertise of the modelers.

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Appendix KKTs, node structure, data, and additional results

This model is programmed in GAMS using the MCP format and it is solved using the PATH solver (Ferris and Munson, 2000).

1 Producer optimality conditions

The producer's profit maximization problem has the following Karush-Kuhn-Tucker conditions (KKTs) of optimality that are obtained after deriving the Lagrangian function for each producer with respect to its decision variables and dual variables of constraints.

$$
\begin{aligned}
&0 \le \left(\frac{1}{1+r_f}\right)^a \cdot \left[-p_{ae}^E + \frac{\partial C_{af}^P}{\partial y_{afe}} + trans_{afe}^E \cdot \kappa_f\right] \\
&+\alpha_{af}^P \cdot \kappa_f + \frac{plength}{2} \cdot \alpha_f^{res} \cdot \kappa_f + \alpha_{afe}^{cap^{TE}} \cdot \kappa_f \qquad \perp y_{afe} \ge 0
\end{aligned} \tag{16}
$$

$$
0 \le \left(\frac{1}{1+r_f}\right)^a \cdot Cinv_{afc}^{TC} - \sum_{a'>a} \alpha_{afc}^{cap^{TC}} + \alpha_{afc}^{inv^{TC}} \perp inv_{afc}^{TC} \ge 0 \tag{17}
$$

$$
0 \le \left(\frac{1}{1+r_f}\right)^a \cdot Cinv_{afe}^{TE} - \sum_{a'>a} \alpha_{afe}^{cap^{TE}} + \alpha_{afe}^{inv^{TE}} \perp inv_{afe}^{TE} \ge 0 \tag{18}
$$

$$
0 \le cap_f^P + \sum_{a'<a} inv_{af}^P - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe}\right) \perp \alpha_{af}^P \ge 0 \tag{19}
$$

$$
0 \le \overline{inv}_{af}^P - inv_{af}^P \perp \alpha_{af}^{inv^P} \ge 0 \tag{20}
$$

$$
\begin{aligned}
&0 \le res_f - \sum_{a \ne startyear} \Big[\Big(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \\
&+\sum_c \kappa_f \cdot x_{(a-1)fc} + \sum_e \kappa_f \cdot y_{(a-1)fe}\Big) \cdot \frac{plength}{2}\Big] \perp \alpha_f^{res} \ge 0
\end{aligned} \tag{21}
$$

$$
0 \le cap_{fc}^{TC} + \sum_{a'<a} inv_{afc}^{TC} - \kappa_f \cdot x_{afc} \perp \alpha_{afc}^{cap^{TC}} \ge 0 \tag{22}
$$

$$
0 \le cap_{fe}^{TE} + \sum_{a'<a} inv_{afe}^{TE} - \kappa_f \cdot y_{afe} \perp \alpha_{afe}^{cap^{TE}} \ge 0 \tag{23}
$$

$$
\begin{aligned}
&0 \le mc\_int_{af} = mc\_int_{(a-1)f} \\
&+mc\_slp_{(a-1)f} \cdot \kappa_f \cdot mc\_int\_var_f \cdot \left(\sum_c x_{(a-1)fc} + \sum_e y_{(a-1)fe}\right), \\
&mc\_int_{af} \ (free)
\end{aligned} \tag{24}
$$

2 Exporter optimality conditions

The exporter's profit maximization problem has the following Karush-Kuhn-Tucker conditions (KKTs) of optimality that are obtained after deriving the Lagrangian function for each exporter with respect to its decision variables and dual variables of constraints.

$$0 \le \left(\frac{1}{1+r_e}\right)^a \cdot \left[-p_{ac}^C + p_{ae}^E + fee_{ae} \cdot \kappa_e + searate_{aec} \cdot \kappa_e\right] + \mu_{ae}^E \cdot \kappa_e + \tau_{ec} \cdot \pi_{aE_{CHN}} \cdot \kappa_e \perp z_{aec} \ge 0 \tag{25}$$

$$0 \le \left(\frac{1}{1+r_e}\right)^a \cdot Cinv_{ae}^E - \sum_{a'>a} \mu_{ae}^E + \mu_{ae}^{inv^E} \perp inv_{ae}^E \ge 0 \tag{26}$$

$$0 \le cap_e^E + \sum_{a'<a} inv_{ae}^E - \sum_c \kappa_e \cdot z_{aec} \perp \mu_{ae}^E \ge 0 \tag{27}$$

$$0 \le \overline{inv}_{ae}^E - inv_{ae}^E \perp \mu_{ae}^{inv^E} \ge 0 \tag{28}$$

$$0 \le China\_lic_{aE_{CHN}} - \sum_{NoChina(c)} z_{aec} \cdot \kappa_e \perp \pi_{aE_{CHN}} \ge 0 \tag{29}$$

3 Final demand formulation

<u>Market Clearing</u>

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

$$p_{ac}^C - p_{ac}^C\left(\sum_f x_{afc}, \sum_e z_{aec}\right) = 0 \quad , p_{ac}^C \ (free) \tag{30}$$

Equation (22) clears sales of the producer to the exporter. Its dual variable gives the price at which the exporter receives the coal from the producer, p_{ae}^E.

$$0 = y_{afe} - \sum_c z_{aec} \quad , p_{ae}^E \ (free) \tag{31}$$

Table A.1: Nodes of COALMOD-World

Country	Producers	Regions	Exporters	Port	Consumers	Regions	Port
Australia	*P_AUS_QLD*	Queensland	*E_AUS_QLD*	Gladstone	*C_AUS*		*No*
	P_AUS_NSW	New South Wales	*E_AUS_NSW*	Botany Bay			
Brazil					*C_BRA*		Fortaleza
Canada	*P_CAN*				*C_CAN*	Ontario	No
Chile					*C_CHL*		Mejillones
China	*P_CHN_SIS*	Gansu, Inner Mongolia, Hebei, Ningxia, Shaanxi, Shaaxi, Shanxi	*E_CHN*	Qinhuangdao	*C_CHN_Northeast*	Heilongjiang, Jilin, Liaoning	No
	P_CHN_Northeast	Heilongjiang, Jilin, Liaoning, Tianjin			*C_CHN_Main*	Beijing, Tianjin, Hebei, Henan, Shandong, Tianjin	No
	P_CHN_HSA	Anhui, Bejing, Fujian, Henan, Jiangsu, Jiangxi, Shandong, Zhejiang			*C_CHN_Eastern*	Anhui, Jiangsu, Hubei, Shanghai, Zhejiang	Shanghai/Ningbo
	P_CHN_YG	Chongqing, Guangxi, Guizhou, Guizhou, Hubei, Hunan, Sichuan, Yunnan			*C_CHN_South*	Chongqing, Fujian, Guangdong, Guangxi, Guizhou, Hong Kong, Hunan,Jiangxi, Sichuan	Guangzhou
					C_CHN_SIS	Shanxi, Shaaxi, Inner Mongolia	No
Colombia	*P_COL*		*E_COL*	Cartagena			
Denmark					*C_DNK*		Aalborg
Finland					*C_FIN*		Kotka
Germany					*C_DEU*		Rotterdam + land transport
India	*P_IND_North*	Jharkhand, Madhya Pradesh, Chhattisgarh, West Bengal			*C_IND_East*	Bihar, Chhatisgarh, Jharkhand, Orissa, West Bengal	No
	P_IND_Orissa	Orissa			*C_IND_North*	Delhi, Punjab, Rajasthan, Uttar Pradesh	No
	P_IND_West	Maharashtra			*C_IND_West*	Gujarat, Madhya Pradesh, Maharashtra	Kandla
	P_IND_South	Andhra Pradesh			*C_IND_South*	Andhra Pradesh, Karnataka, Tamil Nadu	Chennai
Indonesia	*P_IDN*		*E_IDN*	Surabaya	*C_IDN*		No
Israel					*C_ISR*		Ashdod
Italy					*C_ITA*		Taranto
Japan					*C_JPN*		Yokohama
Kazakhstan	*P_KAZ*	Ekibastuz	*E_RUS_West*	Ust-Luga	*C_KAZ*		No
Korea					*C_KOR*		Ulsan
Malaysia					*C_MYS*		Port Klang
Mexico					*C_MEX*		Manzanillo
Mongolia	*P_MNG*						
Morocco					*C_MAR*		Mohammedia
Mozambique	*P_MOZ*		*E_MOZ*	Maputo			
Netherlands/ France/Belgium					*C_NFB*	Netherlands, France, Belgium	Rotterdam
Philippines					*C_PHL*		Manila
Poland	*P_POL*		*E_POL*	Gdansk	*C_POL*		No
Portugal					*C_PRT*		Sines
Russia	*P_RUS*	Kemerovo/Kuznets	*E_RUS_East*	Vladivostok	*C_RUS_Central*		No
			E_Black_Sea_RUS	Odessa	*C_RUS_Siberia*		No
South Africa	*P_ZAF*		*E_ZAF*	Richards Bay	*C_ZAF*		No
Spain					*C_ESP*		Gijon
Taiwan					*C_TWN*		Kaohsiung
Thailand					*C_THA*		Bangkok
Turkey					*C_TUR*		Mersin + Black sea port
UK					*C_GBR*		Immingham
Ukraine	*P_UKR*	Ukrainian/Russian Donetsk	*E_Black_Sea_UKR*	Odessa	*C_UKR*		No
USA	*P_USA_PRB*	Powder River Basin	*E_USA_SC*	Houston, TX	*C_USA_W*	AK, AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA,WY	No
	P_USA_Rocky	Rocky Mountains	*E_USA_SE*	Norfolk, VA	*C_USA_NC*	IL, IN, IA, KS, MI, MN, NE, MO, ND, OH, SD, WI	No
	P_USA_ILL	Illinois Basin	*E_USA_W*	Portland, OR	*C_USA_SC*	AR, LA, OK, TX	No
	P_USA_APP	Appalachian			*C_USA_SE*	AL, DE, DC, FL, GA, KY, MD, MS, NC, SC, TN, VA, WV	Mobile
					C_USA_NE	CT, ME, MA, NH, NJ, NY, PA, RI, VT	No
Venezuela	*P_VEN*		*E_VEN*	Puerto la Cruz			
Vietnam	*P_VNM*						

Table A.2: Various input parameters for COALMOD-World production nodes.

	Prod. capacity 2010 (Mtpa)	Reserves (Mt)	Invest-ment costs ($/tpa)	Max. capacity expansion per 5 year (Mtpa)	Prod. cost function intercept 2010 ($/t)	Prod. cost function slope ($/t*t)	Mine mortality rate (%)
US PRB	525	112,555	40	100	10	0.019	8
US Rocky	79	20,704	60	26	30	0.0633	1
US ILL	115	82,887	50	34	40	0.1128	3
US APP	336	54,572	70	64	40	0.119	10
Colombia	75	6,229	50	30	39	0.1333	15
Venezuela	10	479	50	10	41	1.346	6
Poland	71	13,997	80	5	41	0.831	2
Ukraine	45	16,271	70	10	31	0.6889	7
Kazakhstan	100	28,145	40	15	15	0.147	20
Russia	190	49,078	50	51	15	0.1737	4
South Africa	267	48,740	50	40	20	0.1124	2
IND North	281	35,663	40	60	9	0.1709	1
IND Orissa	123	14,416	40	30	11	0.1302	2
IND West	53	7,134	40	10	22	0.0759	5
IND South	58	6,755	40	10	23	0.344	5
Vietnam	62	150	60	10	12	0.327	60
Indonesia	340	13,000	35	90	23	0.0794	3
CHN SIS	1573	213,400	60	300	21	0.0267	0.8
CHN Northeast	121	15,900	60	50	26	0.2	1
CHN HSA	564	4,700	60	70	30	0.0514	1
CHN YG	450	36,800	60	30	25	0.1111	14
AUS QLD	85	24,764	40	20	25	0.5882	5
AUS NSW	119	13,829	50	20	30	0.3782	8
Mongolia	17	1,170	60	20	30	0.2	10
Mozambique	5	212	80	15	45	0.05	10

4 Detailed results

Table A.3: Results of COALMOD-World: consumption, domestic supply, and imports by consuming country and scenario in 2010, 2020, 2030, and 2040.

	Stagnation scenario [Mt]								2°C scenario [Mt]					
	2010		2020		2030		2040		2020		2030		2040	
Dest	Imp	Dom	Imp	Dom	Imp	Dom	Imp	Dom	Imp	Dom	Imp	Dom	Imp	Dom
AUS	0	63	0	57	0	50	0	41	0	53	0	24	0	10
BRA	5	0	6	0	7	0	9	0	5	0	5	0	5	0
CAN	9	0	8	0	6	0	6	0	6	0	3	0	4	0
CHL	8	0	8	0	11	0	13	0	8	0	7	0	8	0
CHN	95	2404	229	2285	278	2229	168	2200	218	2182	313	1567	286	1239
DEU	31	0	26	0	14	0	8	0	23	0	8	0	6	0
DNK	4	0	4	0	2	0	1	0	3	0	1	0	1	0
ESP	10	0	8	0	4	0	3	0	7	0	2	0	2	0
FIN	5	0	3	0	2	0	1	0	3	0	1	0	1	0
GBR	20	0	15	0	9	0	5	0	14	0	5	0	4	0
IDN	0	58	0	65	0	76	0	86	0	60	0	42	0	31
IND	63	488	165	587	326	740	469	945	135	567	157	569	171	541
ISR	9	0	8	0	4	0	2	0	7	0	2	0	2	0
ITA	14	0	12	0	7	0	4	0	11	0	4	0	3	0
JPN	123	0	104	0	97	0	85	0	96	0	40	0	8	0
KAZ	0	61	0	56	0	53	0	53	0	51	0	27	0	18
KOR	83	0	70	0	61	0	50	0	64	0	29	0	12	0
MAR	4	0	5	0	5	0	6	0	4	0	3	0	3	0
MEX	9	0	9	0	12	0	15	0	9	0	8	0	8	0
MYS	21	0	24	0	27	0	31	0	21	0	15	0	11	0
NFB	22	0	18	0	10	0	6	0	16	0	6	0	4	0
PHL	11	0	12	0	12	0	14	0	11	0	8	0	5	0
POL	0	71	0	58	0	33	0	19	0	52	0	18	0	13
PRT	4	0	4	0	2	0	1	0	3	0	1	0	1	0
RUS	30	69	36	59	33	64	29	65	24	59	19	25	14	19
THA	17	0	16	0	18	0	21	0	15	0	10	0	7	0
TUR	16	0	15	0	14	0	14	0	14	0	7	0	5	0
TWN	62	0	62	0	68	0	79	0	60	0	40	0	28	0
UKR	19	19	30	5	30	3	30	3	26	5	16	0	11	0
USA	0	886	0	762	0	646	0	586	0	624	0	332	0	378
ZAF	0	187	0	185	0	177	0	167	0	179	0	140	0	110

Table A.4: Results of COALMOD-World: domestic supply and exports by producing country and scenario in 2010, 2020, 2030, and 2040.

	Stagnation scenario [Mt]								2°C scenario [Mt]					
	2010		2020		2030		2040		2020		2030		2040	
Prod	Exp	Dom	Exp	Dom	Exp	Dom	Exp	Dom	Exp	Dom	Exp	Dom	Exp	Dom
AUS	93	63	105	57	115	50	119	41	94	53	78	24	58	10
CHN	20	2404	8	2285	0	2229	0	2200	51	2182	0	1567	0	1239
COL	60	0	112	0	136	0	139	0	70	0	60	0	43	0
IDN	270	58	284	65	285	76	237	86	272	60	270	42	238	31
IND	0	488	0	587	0	740	0	945	0	567	0	569	0	541
KAZ	30	61	36	56	33	53	29	53	24	51	19	27	14	18
MNG	17	0	43	0	42	0	16	0	35	0	29	0	23	0
MOZ	4	0	10	0	9	0	0	0	9	0	7	0	0	0
POL	0	71	0	58	8	33	23	19	0	52	1	18	0	13
RUS	71	69	102	59	106	64	108	65	87	59	77	25	67	19
UKR	15	19	34	5	34	3	34	3	29	5	29	0	17	0
USA	19	886	48	762	156	646	207	586	21	624	8	332	9	378
VEN	5	0	10	0	14	0	14	0	9	0	8	0	3	0
VNM	18	0	0	0	0	0	0	0	0	0	0	0	0	0
ZAF	72	187	106	185	126	177	146	167	102	179	126	140	136	110
Sum	694		898		1064		1072		803		712		608	

Table A.5: Trade flows in COALMOD-World (in Mtpa).

From	To	2010	2020		2030		2040	
			Stag. scen.	2°C scen.	Stag. scen.	2°C scen.	Stag. scen.	2°C scen.
USA Appalachia	Canada	9	8	6	6	3	6	4
South America	Europe	65	28	43	0	0	0	0
Kazakhstan	Russia (Central)	30	36	24	33	19	29	14
Russia & Ukraine	Ukraine	18	30	26	30	16	30	11
Russia	Europe	23	18	10	28	20	4	18
Russia	Turkey	26	23	21	19	10	16	7
Russia (via Far East)	OECD Asia	20	36	35	36	3	49	0
South Africa	Europe & West Mediterranean	22	4	3	0	0	0	0
South Africa	India	50	102	99	126	126	146	136
Vietnam	China	18	0	0	0	0	0	0
Indonesia	India	9	53	27	139	23	206	34
Indonesia	Asia (except India)	244	231	245	147	247	31	204
China	S. Korea	20	8	51	0	0	0	0
Australia	India & Thailand	0	16	15	18	10	21	7
Australia	Asia (except India & Thailand)	93	89	79	97	68	98	51
Mongolia	China	17	43	35	42	29	16	23
Mozambique	India	4	10	9	9	7	0	0
South America	Asia	0	94	24	150	67	152	43
USA West	Asia	0	0	0	125	0	199	0
USA Appalachia	Europe	5	17	4	2	0	0	0
Poland	Europe	0	0	0	8	1	23	0
Russia	China	0	0	0	0	32	0	30
Black Sea	Europe & West Mediterranean	0	28	25	19	11	10	5
Indonesia	Chile, Brazil, Mexico	17	0	0	0	0	0	0
Russia	Chile, Brazil, Mexico	0	0	0	8	15	34	13
USA West	Chile, Brazil, Mexico	5	23	10	22	5	3	5
South America	Chile, Brazil, Mexico	0	0	13	0	1	0	3