AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Crawford School of Public Policy

Centre for Climate Economic & Policy

Market power rents and climate change mitigation: a rationale for coal taxes?

CCEP Working Paper 1507
Aug 2015

Philipp M. Richter
German Institute for Economic Research (DIW Berlin)

Roman Mendelevitch
German Institute for Economic Research (DIW Berlin)

Frank Jotzo
Crawford School of Public Policy, The Australian National University

Abstract
In this paper we investigate the introduction of an export tax on steam coal levied by an individual country (Australia), or a group of major exporting countries. The policy motivation would be twofold: generating tax revenues against the background of improved terms-of-trade, while CO_2 emissions are reduced. We construct and numerically apply a two-level game consisting of an optimal policy problem at the upper level, and an equilibrium model of the international steam coal market (based on COALMOD-World) at the lower level. We find that a unilaterally introduced Australian export tax on steam coal has little impact on global emissions and may be welfare reducing. On the contrary, a tax jointly levied by a "climate coalition" of major coal exporters may well leave these better off while significantly reducing global CO_2 emissions from steam coal by up to 200 Mt CO_2 per year. Comparable production-based tax scenarios consistently yield higher tax revenues but may be hard to implement against the opposition of disproportionally affected local stakeholders depending on low domestic coal prices.

Keywords:
Export tax; steam coal; supply-side climate policy; carbon leakage; Australia; Mathematical Program with Equilibrium Constraints (MPEC)

JEL Classification:
Q48, F13, Q58, Q41, C61

Suggested Citation:
Richter, P.M., Mendelevitch R. and Jotzo, F. (2015), Market power rents and climate change mitigation: a rationale for coal taxes?, CCEP Working Paper 1507, Aug 2015. Crawford School of Public Policy, The Australian National University.

Address for Correspondence:
Philipp M. Richter
DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin
Germany
Tel: +49 (30) 897 89-0
Fax: +49 (30) 897 89-200
Email: prichter@diw.de

The Crawford School of Public Policy is the Australian National University's public policy school, serving and influencing Australia, Asia and the Pacific through advanced policy research, graduate and executive education, and policy impact.

The Centre for Climate Economics & Policy is an organized research unit at the Crawford School of Public Policy, The Australian National University. The working paper series is intended to facilitate academic and policy discussion, and the views expressed in working papers are those of the authors. Contact for the Centre: Dr Frank Jotzo, frank.jotzo@anu.edu.au

Market Power Rents and Climate Change Mitigation: A Rationale for Coal Taxes?

Philipp M. Richter* DIW Berlin

Roman Mendelevitch† DIW Berlin

Frank Jotzo‡ Australian National University

April 16, 2015

Abstract

In this paper we investigate the introduction of an export tax on steam coal levied by an individual country (Australia), or a group of major exporting countries. The policy motivation would be twofold: generating tax revenues against the background of improved terms-of-trade, while CO_2 emissions are reduced. We construct and numerically apply a two-level game consisting of an optimal policy problem at the upper level, and an equilibrium model of the international steam coal market (based on COALMOD-World) at the lower level. We find that a unilaterally introduced Australian export tax on steam coal has little impact on global emissions and may be welfare reducing. On the contrary, a tax jointly levied by a "climate coalition" of major coal exporters may well leave these better off while significantly reducing global CO_2 emissions from steam coal by up to 200 Mt CO_2 per year. Comparable production-based tax scenarios consistently yield higher tax revenues but may be hard to implement against the opposition of disproportionally affected local stakeholders depending on low domestic coal prices.

JEL codes: Q48; F13; Q58; Q41; C61

Keywords: export tax; steam coal; supply-side climate policy; carbon leakage; Australia; Mathematical Program with Equilibrium Constraints (MPEC)

*German Institute for Economic Research (DIW Berlin), Mohrenstr. 58, 10117 Berlin, Germany; Email: prichter@diw.de

†German Institute for Economic Research (DIW Berlin), Mohrenstr. 58, 10117 Berlin, Germany; Email: rmendelevitch@diw.de

‡Crawford School of Public Policy, Australian National University, Lennox Crossing, Canberra, ACT 0200, Australia; Email: frank.jotzo@anu.edu.au

1 Introduction

Coal is both the fossil fuel with the highest carbon intensity per unit of energy, and an energy carrier that is globally abundant (cf. Rogner et al., 2012). If climate change is to be kept within tolerable limits, most of the proven global coal reserves need to remain in the ground (cf. Meinshausen et al., 2009; McGlade and Ekins, 2015). By contrast, over the past years a "renaissance of coal" can be observed (cf. Schernikau, 2010).

Restrictions on coal use by importing countries are difficult to implement and, if successful, are likely to shift rather than reduce global consumption. Moreover, they may put fossil fuel exporters at a disadvantage which reduces their willingness to join a climate treaty in the first place. By contrast, supply-side policies could leave energy exporters better off through improved terms-of-trade and fiscal revenue. This may ease the climate treaty negotiating process and generates funding for the transition toward a low-carbon energy system.

In this paper, we focus on the case of an export tax on coal, investigating both the incentives for implementation, and the implications of withholding export supply. Specifically, we consider a hypothetical export tax on steam coal[1] levied by Australia, the world's second largest steam coal exporter, or alternatively by a group of major exporters.[2] We analyse the short-term and long-term effects on tax revenues, CO_2 emissions, and shifts in global steam coal trade.

Supply-side policies to mitigate climate change have recently gained attention in the literature. Sinn (2008) initiated the discussion by highlighting the specific reaction of resource owners to demand side climate policies due to intertemporal trade-offs: If climate policy became increasingly strict over time, resource owners would rationally react with earlier extraction which, in turn, would ultimately accelerate global warming—a *green paradox*. Consequently, climate policy should tackle the supply side and be designed to slow down the extraction path of fossil fuels or to incentivise the conservation of carbon in

[1] According to the IEA (2013) steam coal includes all hard coal that is not coking coal (used for steel production), as well as sub-bituminous brown coal. Steam coal is mainly used for electricity generation and has by far the largest share in global extraction across the different types of coal.

[2] The implementation of an Australian export tax for climate reasons has been suggested for instance by Peter Christoff: http://theconversation.com/why-australia-must-stop-exporting-coal-9698, and Brett Parris http://theconversation.com/expanding-coal-exports-is-bad-news-for-australia-and-the-world-17937, both accessed on November 20, 2013. An export tax is also discussed for Indonesia, see e.g. http://www.businessweek.com/news/2014-07-24/new-rules-in-indonesia-require-coal-exporters-to-have-licenses, accessed on August 10, 2014, or PwC (2014)

the ground. Harstad (2012) theoretically investigates a compensation scheme for resource-rich countries by introducing a market for extraction rights. Committing to conserve coal deposits *in situ*, a climate coalition can cost-efficiently achieve an emissions reduction without carbon leakage; resource owners in turn generate revenues by selling extraction rights.[3]

In contrast to the proposed compensation mechanisms for reduced extraction, we focus on the complementarity of rent capturing and climate change mitigation, and investigate an export tax on steam coal. On the one hand, tax revenues are generated against the background of improved terms-of-trade—a motive for trade policy well-known from the literature. On the other hand, the implementation of an export tax represents a climate policy instrument as it reduces global coal consumption.

The extent of benefits are ultimately determined by the reaction of market participants. Both short term adjustments (e.g. import substitution effects) and long run reactions (e.g. capacity expansions) of competing exporters and importing countries need to be taken into account. Hence, model-based numerical simulations are necessary to investigate the implications of an export tax and its potential as supply-side climate policy.

We set up the problem as a two-level game. At the upper level, one country, or a group of countries, maximizes the Net Present Value (NPV) of its tax revenues by levying an energy-based tax on exports that is proportional to the carbon content of the exported coal. The lower level is defined by a partial equilibrium model of the international steam coal market represented by optimizing representative agents. It is based on the COALMOD-World model (cf. Haftendorn et al., 2012b; Holz et al., 2015) which replicates global patterns of coal supply, demand and international trade in great detail.[4] It features endogenous investments in production and transportation capacities in a multi-period framework and represents the substitution relation between imports and

[3] Asheim (2013) finds distributional advantages of supply-side policies, which are less prone to carbon leakage. Similarly, Bohm (1993) and Hoel (1994) show that depending on demand and supply price elasticities an optimal mix of demand and supply side policies may help to avoid carbon leakage. Hoel (2013) in turn finds that preventing the extraction of the most expensive reserves reduces overall emission and does not provoke intertemporal leakage. Kalkuhl and Brecha (2013) highlight the importance of the distribution of "climate rents", while Eisenack et al. (2012) find that a global carbon cap may indeed leave resource owners better off compared to a business-as-usual scenario, but depending on the allocation rule.

[4] The literature on international steam coal markets is rather sparse, but recently gained more attention in line with the perception of a renaissance of coal. In the tradition of Kolstad and Abbey (1984), two models of the international steam coal market have been developed using equilibrium modelling techniques, one model by Trüby and Paulus (2012) and the COALMOD-WORLD model (Haftendorn et al., 2012b; Holz et al., 2015). These have been applied to analyse the role of Chinese steam coal transportation on the global market (Paulus and Trüby, 2011), and to investigate different climate policy scenarios (Haftendorn et al., 2012a).

domestic production of steam coal. While the policy maker anticipates the reaction of market participants—and hence the impact on prices and quantities in equilibrium—affected exporters take the tax rate parametrically in their decision process.

We follow the literature and represent the international steam coal market as being competitive (cf. IEA, 2013; Trüby and Paulus, 2012; Haftendorn and Holz, 2010). We further assume that national authorities of major exporting countries may well exert an influence on prices via trade policy, similar to Kolstad and Abbey (1984) and Kolstad and Wolak (1985). We hence investigate the interaction between climate policies and the exertion of market power and contribute to the literature on strategic behaviour on the supply and demand side: Liski and Tahvonen (2004), for instance, construct a game of two strategically acting groups of players: a supply-side cartel and a coalition of importing countries. The latter sets a carbon tax including trade policy elements in order to extract rents from the supplying cartel. Böhringer et al. (2014) show that carbon leakage rates depend on the market power of supply side cartels. In particular, if OPEC acts as a dominant player on the international crude oil market, carbon price may lead to negative carbon leakage within the oil market. Furthermore, Persson et al. (2007) and Johansson et al. (2009) argue that resource owners like OPEC may benefit from a global carbon price if the marginal price is set by other energy carriers which are more carbon-intensive and, hence, more affected by climate policies.

Instead of focussing on demand-side climate policies in the context of supply-side cartels, we investigate how export withholding serving the extraction of market rents can act as climate policy. Our contribution is thereby complementary to Fæhn et al. (2014), who derive the optimal mix of demand and supply side policies for resource-rich Norway. While focusing on the crude oil market, they find that the largest contribution to meet CO_2 reduction targets should be made by withholding oil extraction. In contrast to Fæhn et al. (2014) we focus on the steam coal market and on restricted exports. We further rely on a detailed representation of the supply side including capacity constraints and trade costs. Supply curves are hence endogenously derived and not determined by assumptions on long-term supply price elasticities.

Mathematically, the described two-level problem is a Mathematical Program with Equilibrium Constraints (MPEC). Numerical applications of MPECs can be found in a wide range of disciplines and research questions. In contrast to the analysis of market power with similar players (with identical objective functions) being modelled on both the

upper and lower level (cf. Gabriel and Leuthold, 2010; Siddiqui and Gabriel, 2013; Trüby, 2013), our framework is interested in an economic policy analysis given the reaction of market participants. To the best of our knowledge, there has been no study that numerically investigates the climate and distributional effects of a supply side climate policy instrument (at the upper level) on the international steam coal market (at the lower level). As solution techniques applied to large-scale models are still in a development stage (cf. Gabriel and Leuthold, 2010), we develop an algorithm combining different methods in order to solve the outlined problem.

Our main results suggest a positive and substantial Australian export tax of about 7 USD/tCO_2 that maximizes the NPV of tax revenues. However, we find a strong carbon leakage effect of more than 75% following the reduced Australian exports. Production is mainly increased in importing countries, like India and China. In contrast to the traditional *energy market channel* (cf. Burniaux and Oliveira Martins, 2012), it is not a unilateral reduction of demand for fossil fuels that leads to carbon leakage, but supply-side policy: restrictions of one major exporter increases the world market price for steam coal, which gives an incentive for other producers to increase their supply.

The high leakage effect, together with lower profits of Australian steam coal producers, highlights the disadvantages of a unilaterally introduced export tax. By contrast, a coalition of the four largest exporters, Australia, Colombia, Indonesia and South Africa can benefit from a cooperatively set export tax. Moreover, CO_2 emissions are reduced to a larger extent in line with a smaller carbon leakage rate. We test the sensitivity of the results to the members of the coalition by adding the USA. We find a substantial increase in NPV revenue, while the country's calculated revenue share is marginal. Our results show that changing from an export tax to a production-based tax, which affects domestic-oriented supply and export alike, consistently yields higher optimal tax rates and higher NPV revenues. However, such a tax may be hard to justify before local consumers which depend on a low domestic coal price.

The remainder of the paper is organized as follows. Section 2 presents the model setup and the numerical solution method. Section 3 provides a description of the dataset and analysed scenarios. Results are discussed in Section 4, while Section 5 concludes.

2 Model Description

To investigate the effect of a tax levied by major stream coal exporting countries we consider a two-stage game: An optimal policy problem at the upper, and an equilibrium model of the international steam coal market at the lower level. We assume that the tax is introduced by a country-level economic decision maker g which anticipates the equilibrium reactions of all market participants, namely producers $f \in F$, exporters $e \in E$ and final consumers $c \in C$ of steam coal. In turn, these economic players take the policy decision parametrically.[5] In the following model description we focus on the formulation to represent a coal export tax. The respective formulation for a tax on coal production can be found in the Appendix A.3.

2.1 Upper Level: Policy Maker as Stackelberg-Leader

At the upper level, policy maker g can levy a tax τ_a^E on steam coal exports in periods $a \in A$ in order to maximise the NPV of tax revenues over the model horizon. While the policy maker can decide on the initial tax rate τ_0^E starting in period $a = a'$, the path is predetermined by an annual growth rate of r_τ[6]:

$$\tau_a^E = \tau_0^E \cdot (1 + r_\tau)^{a-a'}. \tag{1}$$

We model the export tax based on the energy content of exported volumes; it is hence proportional to a carbon tax.[7] The policy maker's optimization problem is given by

$$\max_{\tau_0^E} \sum_{aec'} \left(\frac{1}{1 + r_g} \right)^{a-1} \cdot \tau_a^E \cdot EXP_{aec'}, \tag{2}$$

where $EXP_{aec'}$ subsumes total exports of all exporters e being located in decision maker g's territory, and directed towards consumption nodes c', which are outside g's territory. Periodic revenues are discounted at rate r_g.

[5] This Stackelberg-leader-follower relation is a common assumption in the literature (cf. Eisenack et al., 2012) and requires the existence of a credible commitment of the respective policy maker (cf. Brander and Spencer, 1985).

[6] On the one hand, we don't want to restrict the analysis to a constant tax rate but rather allow for an endogenous starting value and a gradual increase. One the other hand, leaving the tax as a free variable for each period could create time inconsistencies. In section 4.1.1 we check the sensitivity of the optimal tax rate regarding the growth rate of the tax.

[7] Note that in COALMOD-World, all coal quantities are expressed in terms of their energy content, or explicitly multiplied by a quality factor to express terms in mass units. For instance, costs of production and transportation are related to mass units.

2.2 Lower Level: An Equilibrium Model of the International Steam Coal Market

At the lower level, two stylized types of players, namely producers and exporters, are represented by profit maximizing behaviour under specific operational and technical constraints.[8] Producer f can deliver its coal to local consumers and potentially to several exporters e, where the link is exogenously determined in line with geographical proximity. In contrast, each exporter is assigned to one specific producer. In line with empirical findings the steam coal market is modelled as being perfectly competitive (cf. Haftendorn and Holz, 2010; Trüby and Paulus, 2012; IEA, 2013): No individual producer or exporter can exert market power on consumers c that are represented by inverse demand functions. Regional prices are endogenously determined in accordance with market clearing conditions. Hence, substitution between imports and domestic production of steam coal are endogenously determined.

Furthermore, the model features endogenous investment into production and transportation capacities. Once an expansion is profitable, an investment decision is taken. The capacity is increased and becomes operational in the subsequent period. We take into account quality differences of steam coal across production regions, and assume marginal production costs to increase as well as production capacity to decrease with cumulative extraction and without further investments—a *mine mortality mechanism*.

2.2.1 A Producer's Problem

Producer f is characterized by the quality κ_f and reserves res_f of its coal deposits; by its initial periodic capacity of extraction cap_f^P as well as by the transport costs to local consumers $trans_{afc}^C$ and assigned exporters $trans_{afe}^E$. Moreover, costs of capacity expansions and the maximum periodic investment possibilities are producer-specific.

The objective of producer f is to maximise its profits discounted at rate r_f. Accord-

[8] The lower level is based on COALMOD-World, a large-scale multi-period equilibrium model with a full representation of the value chain of the international steam coal market. The model has been derived and described in detail in Haftendorn et al. (2012b), and thoroughly updated in Holz et al. (2015). We adjust the model to our research question, and reformulate it according to the requirements of each of the applied solution methods (see section 2.3). In the Appendix we provide a list of endogenous variables in A.1, and the complete model formulation stated as equilibrium problem by Karush-Kuhn-Tucker (KKT) conditions in A.2.

ingly,

$$\max_{x_{afc},\, y_{afe},\, inv^P_{af},\, inv^{TC}_{afc},\, inv^{TE}_{afe}} \Pi_f = \sum_a \left(\frac{1}{1+r_f}\right)^{a-1} \cdot \Bigg[\tag{3}$$

$$\sum_c p^C_{ac} \cdot x_{afc} + \sum_e p^E_{ae} \cdot y_{afe} - Cprod_{af}[x_{afc},\ y_{afe}]$$

$$- \sum_c trans^C_{afc} \cdot \kappa_f \cdot x_{afc} - \sum_e trans^E_{afe} \cdot \kappa_f \cdot y_{afe}$$

$$- Cinv^P_{af} \cdot inv^P_{af} - \sum_c Cinv^{TC}_{afc} \cdot inv^{TC}_{afc} - \sum_e Cinv^{TE}_{afc} \cdot inv^{TE}_{afe} \Bigg],$$

with revenues being generated from selling coal to local consumers, x_{afc} at price p^C_{ac} and to exporters y_{afe} at price p^E_{ae}. The remaining terms of Eq. (3) depict the costs of production $Cprod_{af}$, the costs of transportation to the respective buyers $trans^C_{afc}$ and $trans^E_{afe}$ and the costs of potential investments into expanding the capacity of production $Cinv^P_{af}$ and transportation to consumers $Cinv^{TC}_{afc}$ and ports $Cinv^{TE}_{afc}$ — all multiplied with respective decision variable. Note that, while coal is sold in terms of its energy content, costs of production and transportation incur in terms of mass units; hence, the multiplication by producer's quality factor κ_f, which reflects the producer-specific conversion rate.

We assume a production cost function $Cprod_{af}$ that is quadratic in extracted quantities leading to linear periodic marginal costs of extraction:

$$MC_{af} = mc^{int}_{af} + mc^{slp}_f \cdot \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe}\right), \tag{4}$$

where the intercept increases in cumulative extraction in former periods according to Eq. (5) with δ_f being a producer-specific shift parameter:

$$mc^{int}_{af} = mc^{int}_{a-1f} \cdot \delta_f \cdot \kappa_f \cdot \left(\sum_c x_{a-1fc} + \sum_e y_{a-1fe}\right). \tag{5}$$

This formulation implies a ranking of extraction from low to high costs deposits and ties periodic extraction.

The optimisation problem is subject to five constraints:[9]

The first constraint (Eq. 6) requires that in each period production cannot exceed the production capacity, determined by the initial capacity, increased by capacity expansions in former periods and reduced by past cumulative production replicating the mortality of

[9] For each constraint, the respective dual variable, i.e. Langrangian multiplier, is given in parentheses.

mines,

$$cap_f^P + \sum_{a'<a} \left[inv_{a'f}^P - \left(\sum_c \kappa_f \cdot x_{a'fc} + \sum_e \kappa_f \cdot y_{a'fe} \right) \cdot mc_int_var_f \right] \geq$$
$$\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \qquad (\alpha_{af}^P). \tag{6}$$

Similarly, the second and third constraint (Eq. 6 and 7) require that transportation capacities to consumers and exporters, respectively, are not exceeded. Hence,

$$cap_{fc}^{TC} + \sum_{a'<a} inv_{a'fc}^{TC} \geq \kappa_f \cdot x_{afc} \qquad (\alpha_{afc}^{TC}), \tag{7}$$

$$cap_{fe}^{TE} + \sum_{a'<a} inv_{a'fe}^{TE} \geq \kappa_f \cdot y_{afe} \qquad (\alpha_{afe}^{TE}). \tag{8}$$

Fourth (Eq. 9), cumulative extraction over the whole model horizon must not exceed available reserves,

$$res_f \geq \sum_a \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \qquad (\alpha_f^{res}), \tag{9}$$

and finally (Eq. 10), periodic investments in capacity expansions are limited according to

$$inv_{af}^P \leq \overline{inv}_f^P \qquad (\alpha_{af}^{inv^P}). \tag{10}$$

2.2.2 An Exporter's Problem

Exporter e in turn maximizes the NPV of its profits by deciding on the periodic amount of exported steam coal z_{aec} to consumer c, and on expansions of export capacity inv_{ae}^E. Accordingly,

$$\max_{z_{aec},\, inv_{ae}^E} \Pi_e = \sum_a \left(\frac{1}{1+r_e} \right)^{a-1} \cdot \Big[\sum_c p_{ac}^C \cdot z_{aec} \tag{11}$$
$$- \sum_c \left(p_{ae}^E \cdot z_{aec} + fee_e \cdot \kappa_e \cdot z_{aec} + sea_{aec} \cdot \kappa_e \cdot z_{aec} + \tau_a^E \cdot z_{aec'} \right) - Cinv_{ae}^E \cdot inv_{ae}^e \Big].$$

Exports are sold at price p_{ac}^C to consumer c, whereas costs incur from purchasing the coal at price p_{ae}^E, from port fees fee_e and from transportation costs sea_{aec}. Both these fixed and variable trade costs are based on mass units, hence the multiplication by origin-specific quality factor κ_e. Deviating from the original formulation in Haftendorn et al. (2012b) and

Holz et al. (2015), in our formulation an additional export tax has to be paid, if exporter e is located in the territory of decision maker g. Finally, investments in export capacity, inv^E_{ae} can be made at per unit expansion costs of $Cinv^E_{ae}$.

Two constraints need to be taken into account: a restriction on the export capacity

$$cap^E_e + \sum_{a<a'} inv^E_{a'e} \geq \sum_c \kappa_e \cdot z_{aec} \qquad (\mu^E_{ae}), \tag{12}$$

and a maximum periodic investment level to expand this export capacity

$$inv^E_{ae} \leq \overline{inv}^E_{ae} \qquad (\mu^{inv^E}_{ae}). \tag{13}$$

Parameter cap^E_e denotes the initial export capacity, while $\overline{inv}^E_{ae}$ determines the maximum periodic investment possibilities of exporter e.

2.2.3 Market Clearing

The model is closed by means of inverse demand functions and market clearing conditions. Together they endogenously determine the prices paid by exporters and consumers according to

$$\sum_f y_{afe} = \sum_c z_{aec} \qquad (p^E_{ae}) \tag{14}$$

$$p^C_{ac} = int^D_{ac} + b_{ac} \cdot \left(\sum_f x_{afc} + \sum_e z_{aec} \right) \qquad (p^C_{ac}). \tag{15}$$

2.3 Solution Algorithm

In mathematical terms, the two-level problem described by Eqs. (1)-(15) is a MPEC. Solving MPECs is a demanding task due the combination of optimization at the upper, and an equilibrium problem at the lower level which pose fundamentally different restrictions on potential solutions.[10]

The most readily available option to solve MPECs using the software GAMS is to rely on the commercial solver NLPEC. The upper level, in our case represented by Eq. 2, together with a KKT reformulation of the lower level problem constitute the MPEC that is input to the NLPEC solver (see Appendix A.2 for the full set of KKT conditions given

[10] See Luo et al. (1996) who provide an overview of different solution techniques for MPECs that has been updated by Siddiqui (2011).

by Eqs. A.1-A.18). This solver works computationally fast and has been applied in the literature (cf. Huppmann and Holz, 2012; Trüby, 2013).

However, this solution method is opaque and does not necessarily provide the user with the globally optimal solution. In order to circumvent drawbacks of the NLPEC method, we vary the upper and lower bounds of decision variable τ_0^E in a multitude of runs to obtain different local optima as candidate solutions. We pick the candidate with the highest objective value as our global optimum. As a robustness check we take a one level formulation of our problem and compute equilibrium results for a grid of different initial tax rates. The shape of the resulting distribution of tax rates suggests that the optimum obtained from the NLPEC runs is indeed global.

An established alternative is to reformulate the lower level problem into a Mixed-Integer Problem (MIP) by using disjunctive constraints (see Fortuny-Amat and McCarl, 1981 for the original formulation, and Gabriel and Leuthold, 2010 for a recent application). We develop an algorithm that combines the two methods and apply it to smaller datasets. See Appendix A.4 for further details. However, due to extensive computational burdens, we rely on the NLPEC solver for the large-scale numerical application as described in the following section.

3 Model Specification and Scenario Descriptions

3.1 Data Description

We use a detailed dataset which represents all major steam coal producing and consuming countries covering 95% of world coal production in the base year 2010. Some countries are further disaggregated into separated geographical regions in order to allow for within country heterogeneity in resource deposits and transportation costs to consumption areas. This applies to Australia, China, India, Russia and the USA. Overall, we include 25 production, and 40 consumption regions as well as 16 ports of export.[11]

The underlying dataset is collected from various sources and described in detail in Holz et al. (2015). Exemplary, Fig. 1 shows the FOB costs for main production regions implied by our assumptions on production costs in the base year. Trade costs in turn are related to distances measured in nautical sea miles.

[11] A complete list can be found in the Appendix. Note that our dataset incorporates more exporters ($e = 23$) than ports, to account for the case of more than one producing region being assigned to a specific port. By this modelling choice, we avoid any pooling problem due to quality differences across producers.

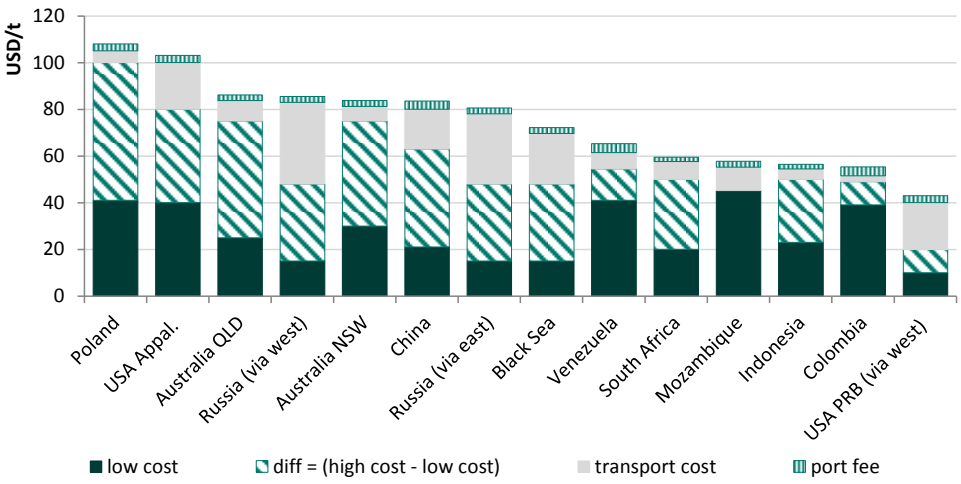


Figure 1: FOB costs in 2010 for export countries in COALMOD-World, in USD/t. *Source: Holz et al. (2015)*

The model solves in five-years steps starting in 2010; results are reported until 2030, while the model horizon is extended by one period in order to allow for profitable investments in the last reported periods.

3.2 Scenario Definitions

Our *"Base Case"* is constructed in line with the New Policy Scenario (NPS) of the World Energy Outlook 2012 (IEA, 2012) which we base our reference consumption levels on.[12] The NPS is a scenario of moderate climate policy, assuming the implementation of current energy and climate policy initiatives. While CO_2 emissions decline in some regions (e.g. by 16% between 2010 and 2035 in OECD countries), global emissions are on an increasing path. Accordingly, global steam coal consumption is projected to rise through 2035. China and India jointly share more than 70% of global coal consumption throughout. In contrast to reference consumption levels, the patterns of production and international trade flows are endogenously determined representing cost-minimization results.

Two export tax scenarios are constructed that deviate in the countries where the tax is levied; results then are compared to the *Base Case*:

- The first scenario *"Tax AUS"* focuses on a unilaterally set export tax on steam coal by Australia.[13] Australia has a large share in international trade of steam coal

[12] Reference consumption levels, reference prices and demand price elasticities are used to derive the linearly approximated inverse demand curve in Eq. (15).

[13] We distinguish the two Australian coal producing regions New South Wales and Queensland. The

(about 16% in 2012 according to the IEA, 2013) and its policies are perceptible on the international market. The default settings further assume a discount rate of tax revenues at 5% ($r_g = 0.05$) as well as a moderate annual tax growth rate of 2.5% ($r_t = 0.025$).

- The second scenario *"Tax Coalition"* analyses the situation of a coordinately set export tax by a coalition of major exporting countries, namely Australia, Indonesia, Colombia and South Africa. Together they have a share in international traded steam coal of 72% in 2012 (cf. IEA, 2013). Both the (common) discount rate and the growth rate of the tax are the same as in *Tax AUS*.

For each export tax scenario, we additionally contrast the results with a production-based tax set by the same group of counties. Moreover we test the sensitivity of the *"Tax Coalition"* scenario to the members of the coalition by adding the USA. For all scenarios, sensitivity runs and robustness checks, we assume the introduction of the tax in the model period 2015 and rule out the anticipation by any model agents: all variables in the previous period 2010 are fixed at *Base Case* levels. We hence avoid any inconsistencies and do not allow for adjusted infrastructure expansions in 2010 in anticipation of the tax rate.

4 Discussion of Results

According to our expectations, the implementation of an export tax on coal would lead to four partial effects. First, coal extraction and exports from the tax-implementing country are reduced. Second, its supply on the domestic market gets more attractive compared to the alternative of exporting; hence, consumption in the tax-setting country increases. Third, international production in all other countries increase: Export competitors compensate for the lower international supply, while net importers rely on domestic production to a larger extent. Finally, with an increase in world coal prices (the terms-of-trade effect), worldwide consumption of coal—and thus global CO_2 emissions—is reduced. These effects translate into a pronounced change in the patterns of trade.

The following discussion of scenario results analyses these tax-induced changes in the patterns of consumption, production and trade relative to the *Base Case* with a particular on CO_2 emissions and carbon leakage.[14]

same tax rate applies to both regions.

[14]Guiding *Base Case* results can be found in Table A.3 in the Appendix.

4.1 Scenario 1: A Unilateral Australian Tax on Coal

Given the optimization problem stated in Eq. (2), the tax revenue maximizing starting value of the Australian export tax is 0.66 USD/GJ. This is a significant level that is equivalent to a carbon tax of 6.7 USD/tCO_2, or a tax of about 18 USD per tonne of Australian steam coal. Given the assumed discount rate of 2.5%, the NPV of tax revenues until 2030 is around 16 bn USD, with only small changes in periodic tax revenues.

Figure 2 shows how Australian consumption, production and exported quantities are affected by this tax introduction. In the *Base Case*, Australian exports increase over time by almost 50% between 2010 and 2030. In *Tax AUS*, however, exports decrease from their 2010 level until 2020, before they remain at the same level for the remaining model years. In every period exports are significantly lower than in the *Base Case*, approaching a level of only 50% in 2030.

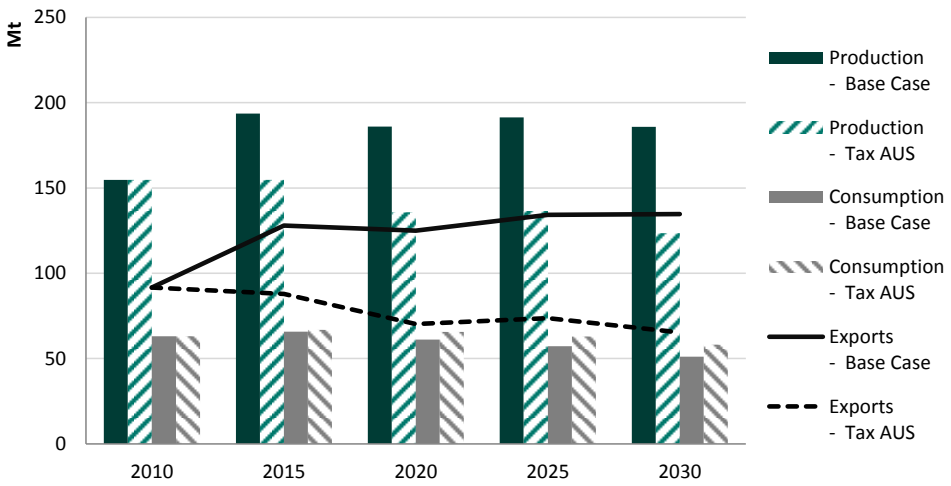


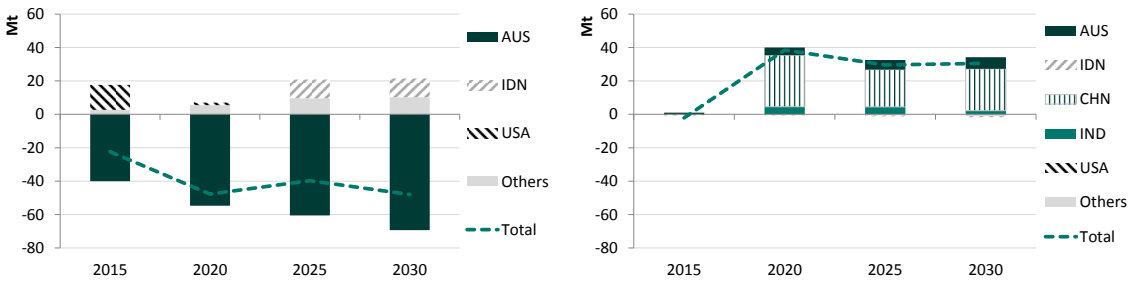
Figure 2: Australian production, consumption and exports in the *Base Case* and in *Tax AUS*, in Mt.

Australian consumption, on the other hand, decreases in both cases but more strongly in the *Base Case* from above 60 Mt in 2010 to 50 Mt in 2030. Since exporting gets relatively more expensive due to the additional costs incurred by the export tax, supply to domestic consumers is encouraged in *Tax AUS*. Here, consumption levels are higher by up to 14% above the *Base Case* value in 2030, in accordance with Australian consumer prices being well below the *Base Case* level. In each period, however, this price difference is smaller than the tax rate.

The effect on Australian consumption is small compared to the export effect, therefore

production levels are reduced almost by the same amount as export levels. The gap between *Base Case* production levels and those under *Tax AUS* increases from less than 40 Mt in 2015 to more than 60 Mt in 2030.

The reaction to an Australian export tax is particularly visible in the production levels of all other countries (RoW). Figure 3 depicts production reactions in detail, divided into supply for the international and the domestic market.



(a) Production destined for export market (b) Production destined for domestic market

Figure 3: Changes in global production relative to the *Base Case*, by supplier, in Mt.

In the year 2015, when the tax is introduced, exporting competitors are not able to rapidly expand their supply as most of them are already running at capacity. This holds true with the exemption of some additional supply from Russia which is redirected from its domestic market, and more significantly from the USA. At the same time the large consumers, namely China and India, are not able to increase their domestic production on short notice neither. It is only by 2020 that the capacity can be expanded and domestic production gains a comparative advantage over high-price imports made possible by sufficient domestic transport capacity.

Similarly, after 2020, international export competitors of Australia increase their supply. After 2025, Indonesia and Russia together compensate for around 25% of reduced Australian exports, while, interestingly, the USA, Colombia and South Africa cannot competitively increase their exports significantly. In the longer run around 35-45 Mt of reduced Australian annual exports remain uncompensated by other net exporting countries. Hence, world steam coal trade is significantly reduced relative to the *Base Case*.

By contrast, global production is reduced only by a small amount, on average by 12 Mt. While in the starting year of the tax, up to 24 Mt of Australian exports remain entirely uncompensated; in later periods reduced exports are compensated by an increase in the domestic production of net importers (import substitution effect), and, to a smaller

extent, by other exporters.

Country-level consumption patterns change for different reasons (see Figure 4). First, importing countries generally suffer from an introduced Australian export tax. In particular, consumption is significantly lower in China and India despite the increase in domestic production. In Taiwan, one can observe an inter-temporal shift in the patterns of consumption with lower consumption in 2020 and 2025, but higher consumption thereafter. Second, as discussed above, consumption in Australia is higher due to shifts from exporting to supplying domestic consumers. Finally, consumption is lower in other exporting countries such as in Russia or Indonesia due to an an increasing pressure to shift supply from the domestic to the export market.

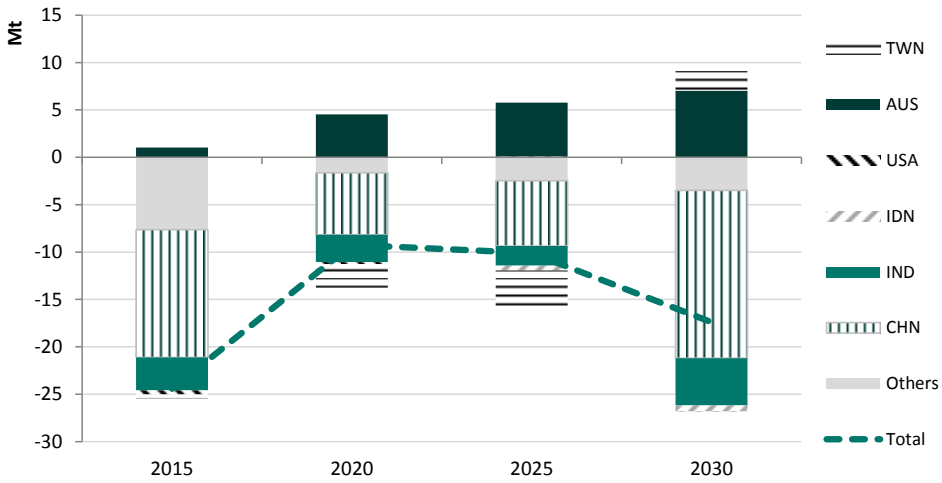


Figure 4: Changes in patterns of global consumption relative to the *Base Case*, in Mt.

In line with consumption, global CO_2 emissions are lower than in the *Base Case*. Yearly emissions decrease by 63 $MtCO_2$ in 2015 which corresponds to 28% of GHG emissions from the Australian energy sector in the 2012.[15] This amount drops to 27 $MtCO_2$ in 2020 but rises to 51 $MtCO_2$ in 2030, again. Given the chosen tax level, emissions from Australian coal drop by on average 150 $MtCO_2$. Compared to average emissions from Australian coal of 558 $MtCO_2$, this is a significant reduction. Note that consumption-based emissions increase in Australia but global emissions decrease in line with global coal consumption.

Figure 5 summarizes the impact of an Australian export tax decomposed into exports and production for the domestic market differentiated between Australia and all other countries. The large shift in global steam coal production and a significant rebound effect

[15]See http://ageis.climatechange.gov.au/, accessed on October 10, 2014.

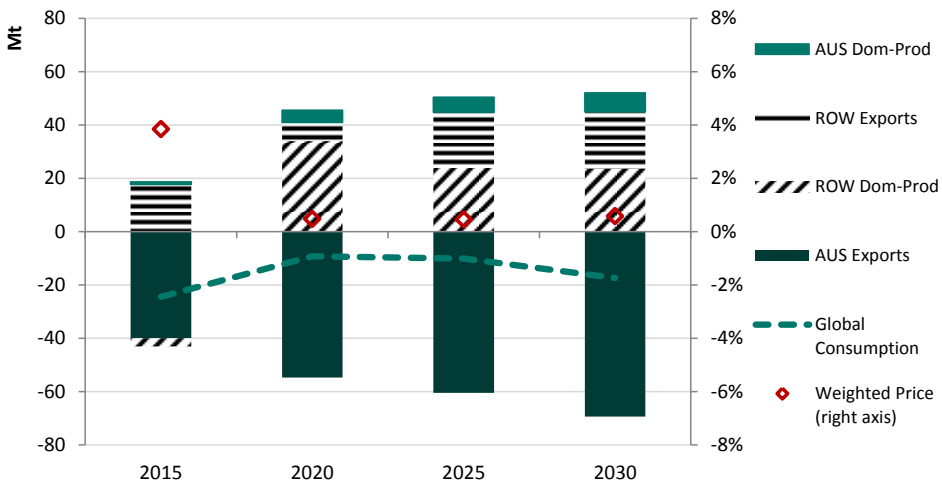


Figure 5: Decomposed impact of an Australian export tax relative to the *Base Case*, in Mt, and change in weighted CIF prices in %.

is observable.[16] The figure also depicts the effect of the tax on average steam coal prices for the consumers. The relative price increase is proportional to the reduction in annual consumption, with an increase of 4% in 2015, when the market cannot adjust to the tax shock, and hardly any price change in the following periods.

In summary, the unilateral introduction of an Australian export tax significantly changes global patterns of consumption, production and exporting, but only has a small impact on global CO_2 emissions.

4.1.1 Sensitivity Analysis: Discount Rate and Tax Growth

The optimal initial tax rate is found to be robust to changes in the discount rate within the range of $r_g \in [0, 0.10]$. For instance, a discount rate of 0% changes the optimal initial tax rate to 6.72 USD/tCO_2 compared to the 6.73 USD/tCO_2 with the default assumption of a discount rate AT 2.5%.

Moreover, we analyse different predetermined annual growth rates of the export tax, i.e. 0% (constant), 2.5% (default; slow increase), 5% and 10% (fast increasing tax rate) as well as -2.5% (decreasing path). Intuitively, the lower the slope the higher the initial tax value. While the initial optimal tax rate decreases monotonically with the growth rate parameter, the function of the NPV of tax revenues is bell shaped (see Figure 6). Among the tested growth parameters, the default setting leads to a slightly lower NPV of tax

[16] In the Appendix, global steam coal trade flows in the year 2030 are depicted for the *Base Case* and both scenarios in their default specification.

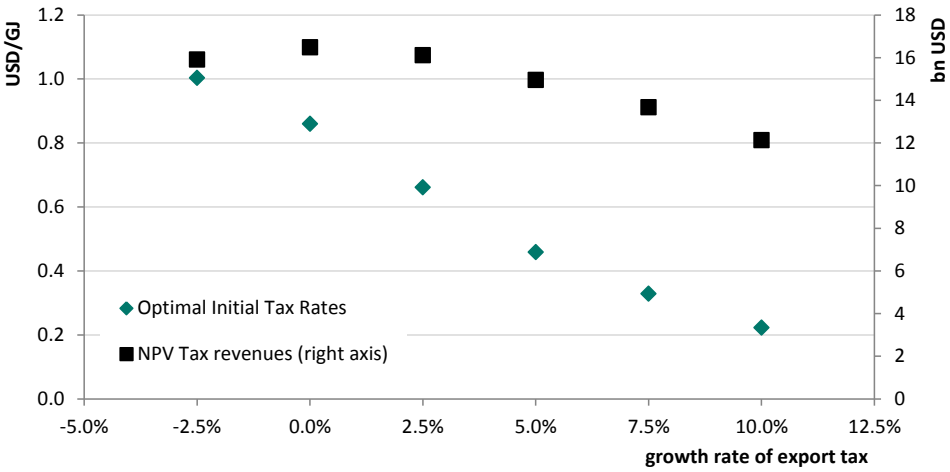


Figure 6: Optimal initial tax rates, in USD/GJ and the NPV of tax revenues, in bn USD, as a function of the growth rate of the export tax, in percentage per annum.

revenues than does the introduction of a constant tax rate over time.

4.1.2 Export vs. Production Tax

The Australian export tax leads to a net reduction of global CO_2 emissions. However, coal consumption is shifted to domestic consumers and Australian emissions consequently increase. Furthermore, export taxes are criticised for their trade-diverting effects. For this reason, we compare our results to an optimally set production tax on coal.[17]

While an export tax serves to hold back supply from international consumers and leads to a shift to domestic consumers, a production tax hits domestic and foreign consumers alike. Figure 7 shows that there exist two pronounced local optima in the NPV of tax revenue. The first one lies in the range of the export tax derived in the previous sections with an initial value of 8.78 USD/tCO_2. Emissions reductions are more pronounced as both Australian exports and consumption levels decline.

The global optimum, however, is reached at a much higher initial tax level of almost 40 USD/tCO_2. Tax revenue is substantially higher; emissions reduced to a larger extent. However, we can see from Figure 7 that welfare, measured as the sum of producer surplus, consumer surplus and tax revenues, is substantially reduced. It is only domestic consumers who carry the tax burden as the production tax rate is prohibitive for any profitable

[17]The introduction of a production tax instead of an export tax requires changes in the model equations which are described in detail in Appendix A.3.

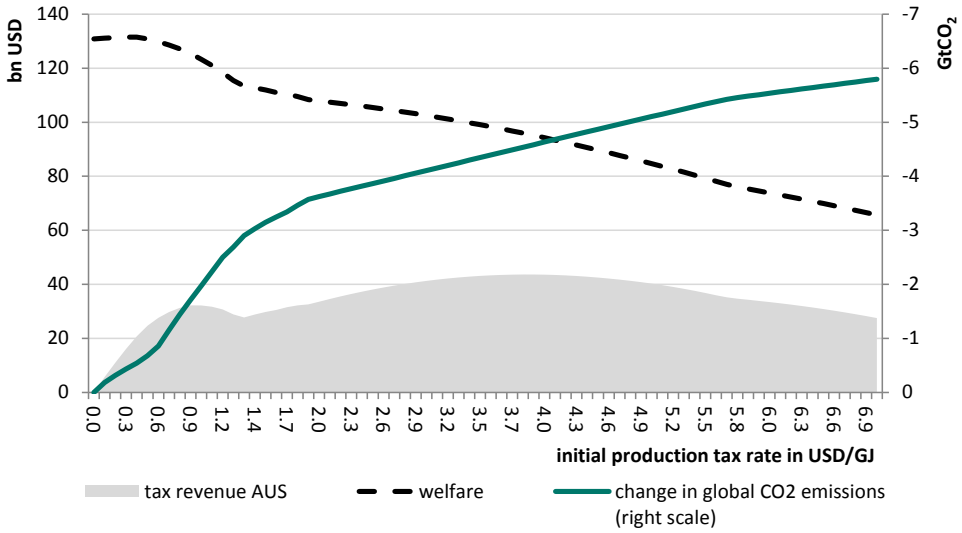


Figure 7: Australian tax revenues and welfare, in bn USD, as well as the reduction in CO_2 emission, in Gt, as a function of the initial production tax rate, in USD/GJ.

exports.[18] Production in 2030, in turn, is reduced to a tenth compared to the *Base Case*.

4.2 Scenario 2: A Jointly Set Coal Tax by Major Exporting Countries

A coordinately set export tax by the largest four exporting countries, Indonesia, Australia, South Africa and Colombia, leads to a stronger terms-of-trade effect and higher tax revenues compared to any unilateral policy action. The optimal tax level (based on the NPV maximization of joint tax revenues) is given by 0.99 USD/GJ. This is approximately 10.1 USD/tCO_2, or 22-26 USD per tonne of exported steam coal (depending on the energy content of the respective coal). The tax rate is significantly higher than the unilaterally introduced Australian export tax.

The NPV of joint tax revenues reaches about 125 bn USD; the Australian share—in the absence of any coalition redistribution scheme—is 16 bn USD, which is similar to the revenues in the unilateral *Tax AUS* case. Figure 8 depicts the NPV of tax revenues as a function of the initial export tax rate and differentiated by coalition members. Depending on the tax level, Indonesia generates 45-65% of the annual tax revenue in this coalition.

Given that the seaborne trade only accounts for around 15% of total consumption,

[18] Up to the maximum, the increase in the tax rate is stronger than the decline in quantities. Note that these results are sensitive to our assumptions on demand price elasticities and the linearly approximation of the inverse demand function around a reference price-quantity equilibrium. Moreover, since Australia is included as exporting country only, there is no alternative supply to the domestic consumers who may want to switch to importing steam coal.

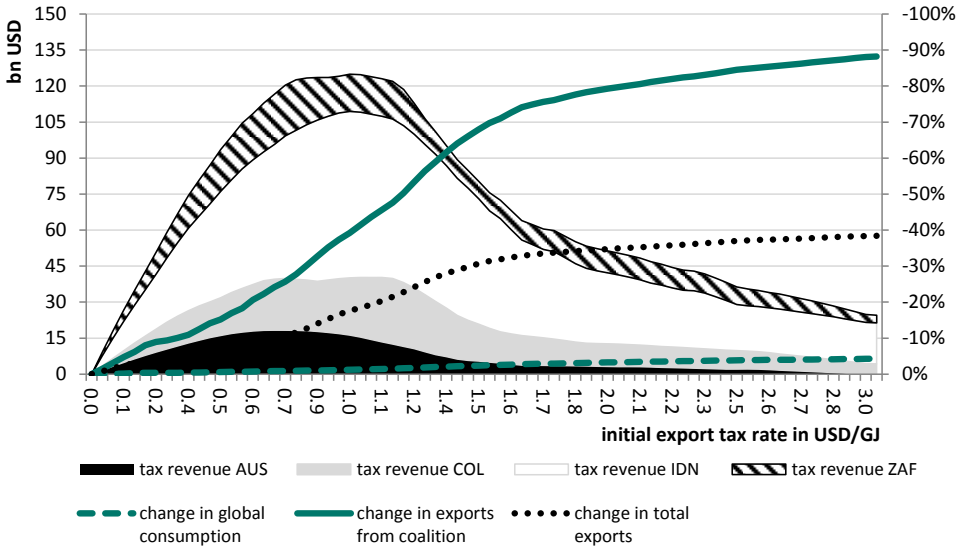


Figure 8: NPV of tax revenues of coalition members, in bn USD, as well as change in global consumption, export for all coalition members and total exports, in percentages, as a function of the starting value of the export tax, in USD/GJ.

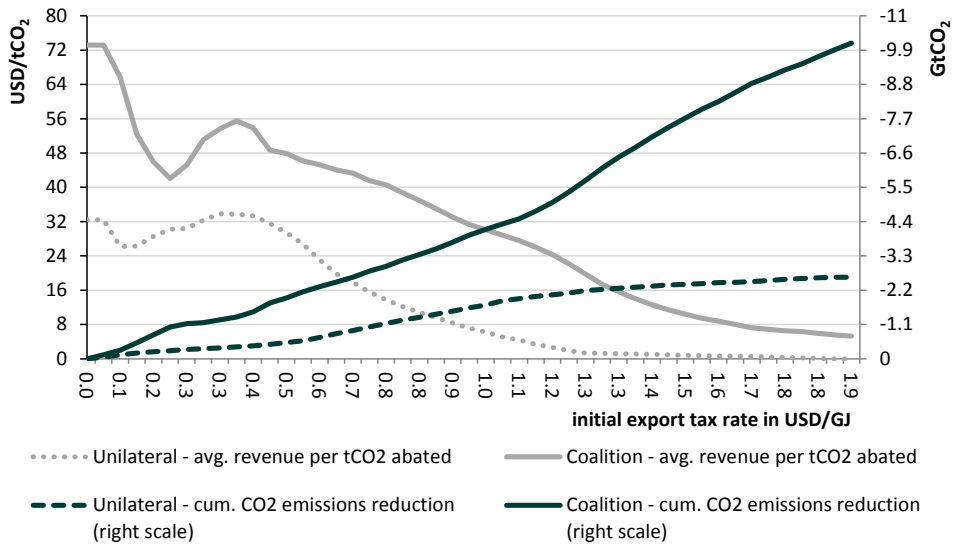


Figure 9: Comparison of average revenues per tonne of CO_2 abated, in USD/tCO_2, and the cumulative CO_2 emissions reduction, in Gt, in *Tax AUS* and *Tax Coalition* as a function of the starting value of the export tax, in USD/GJ.

the introduction of the tax does not have a significant impact on global steam coal consumption, no matter the level of the tax. At the optimal tax level, global coal exports are reduced by 20% while the coalition restrains about 40% of its exports. Figure 9 shows that, for a given tax level, the *Tax Coalition* case always has higher average revenues per tonne of CO_2 avoided (a market power effect) and higher cumulative emissions reductions than the *Tax AUS* case. Note that for the optimal tax rate the level of average additional revenues is at about 19 USD/tCO_2 (at cumulative CO_2 emissions reduction of 900 MtCO_2) for the *Tax AUS* case, while its is 30 USD/tCO_2 (at cumulative CO_2 emissions reduction of 4,100 MtCO_2) for the *Tax Coalition* case.

Taking the Australian perspective, Figure 10 shows how that the maximum tax revenues and welfare level both increased in the situation of a cooperatively acting coalition. This is due to the reduced set of countries that countervail the Australian rent seeking policy setting.

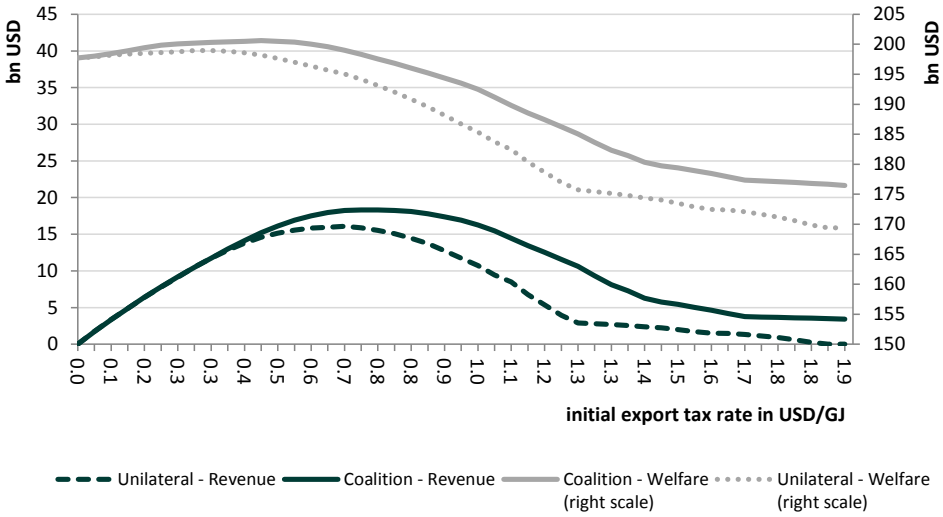


Figure 10: Comparison of Australian tax revenues and welfare (right axis), in bn USD, between the unilateral export tax and the jointly set export tax by major exporters as a function of its starting value, in USD/GJ.

Worldwide, steam coal exports are reduced since no other exporting country can compensate significantly for the supply restrictions of the major four exporters. As in *Tax AUS* the rebound effect is mainly driven by a pronounced increase in production destined for domestic markets. Nevertheless, and as expected, the total rebound effect is less severe, and global consumption is reduced to a larger extent than in the unilateral Australian tax

case. On average, global CO_2 emissions are reduced by 200 $MtCO_2$ per year, compared to yearly reductions of 37 Mt CO_2 in the unilateral case.

Figure 11 summarizes these volume effect of the coalition's export tax, as well as it shows the impact on average consumer prices for coal. The relative price increase is most pronounced in the year the tax is introduced. In 2020 it drops from 8% to 1% but then again steadily increases to 3% in 2030. The price trend is proportional to the restrained supply by the coalition members.

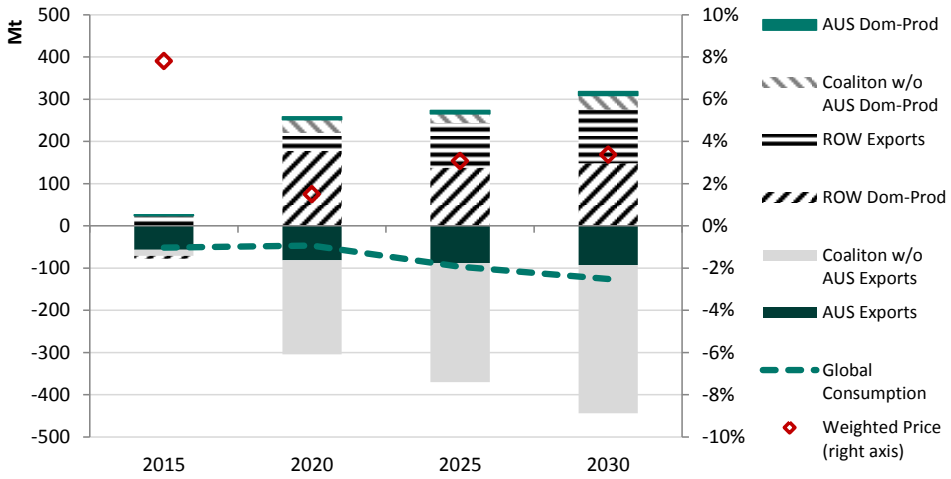


Figure 11: Decomposed impact of an export tax jointly set by the coalition of major exporters relative to the *Base Case*, in Mt, and change in weighted CIF prices in percentages.

4.2.1 Coalition joint by the USA

To check the sensitivity of our results with respect to the members of the coalition, we examine the case with the USA joining the coalition. We find the optimal initial tax level at 12.2 USD/tCO_2 compared to 10.1 USD/tCO_2 in the coalition of the 4 major exporters only.

Total coalition revenues rise to 150 bn USD. While the effect of including the USA into the coalition is quite pronounced—leading to an increase of 2.1 USD/tCO_2 in the optimal tax level, and 25 bn USD of additional revenues—the US' share of revenues is rather small compared to the other members (see Figure 12). This poses the question of how the revenue is to be distributed, which we leave to further research. The high tax puts the price under pressure and leads to an increase of on average 8.5%. Competing exporters and domestic producers are increasingly unable to compensate for the restrained exports which lead to a 3% decrease in global consumption—and thus CO_2 emissions—over the model horizon.

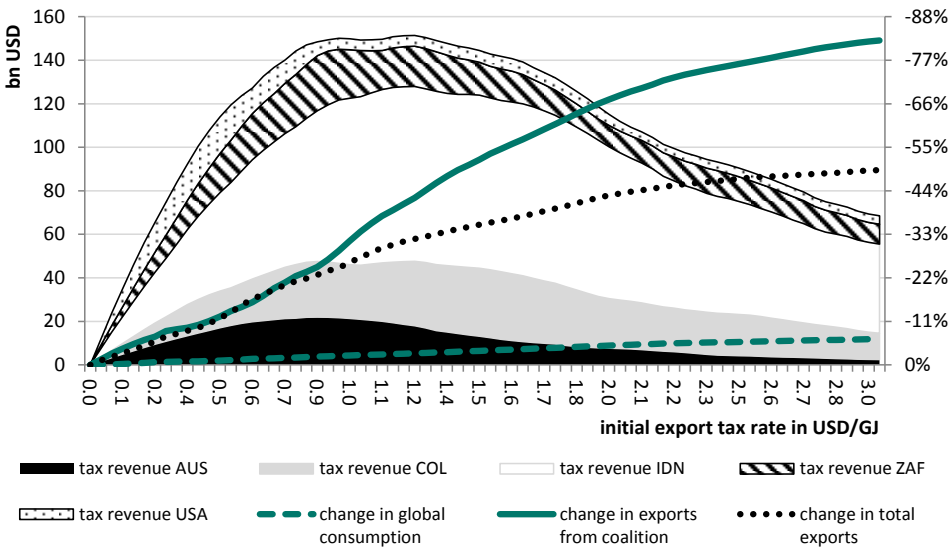


Figure 12: NPV of tax revenues of coalition members, in bn. USD; and change in global consumption, export for all coalition members and total exports, in percentages, as a function of the starting value of the export tax, in USD/GJ.

4.2.2 Coalition: Export vs. Production Tax

A tax levied on both, the domestically oriented production as well as on exports in Colombia, South Africa, Australia, and Indonesia, is a major intervention in the cost structure

of the world steam coal market which affects 17% of global production and 72% of global exports (2010 values from COALMOD-World dataset, based on IEA, 2013). Similar to the unilateral case, we find a higher commonly chosen production tax rate that exceeds coalition's export tax by 20% and reaches a level of 12.2 USD/tCO_2. Figure 13 depicts the decomposition of tax revenues across members and shows how global emissions reduce with the initial production tax level. Notably, tax revenues as a function of the initial tax level peaks twice. Contrary to the unilateral tax scenario, here, the first peak yields the highest revenues.

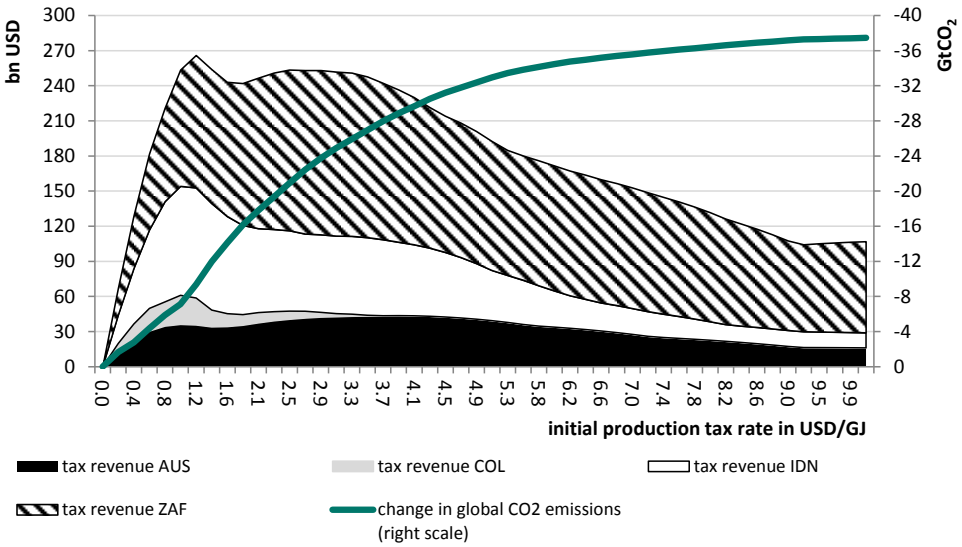


Figure 13: Tax revenues of the coalition's members, in bn USD, and change in global CO_2 emission, in Gt, as a function of the initial common production tax rate, in USD/GJ.

In contrast to an export tax, the coalition's supply to its domestic market is substantially reduced. Overall, both production and export levels are reduced by almost 50% in 2030 relative to the *Base Case*. Cumulative CO_2 emissions can be reduced by 9 Gt. In this scenario South Africa, with its high and increasing domestic coal demand, has a dominant role in the coalition, with almost 50% of the coalition's revenue (compared to 15% in the export tax scenario). The NPV of the coalition's total revenue is 260 bn USD which is twice the amount of the export tax scenario. At the same time, the domestic consumers in the coalition countries are heavily affected by the tax and have to bear an average price increase of 10%, compared to a global average increase of 5%.

4.3 Qualification of Results

The analysis above has some limitations that are briefly discussed in this section.

At the lower level, we rely on a partial equilibrium model of the international steam coal market. Substitution with other fossil fuels is only indirectly taken into account through inverse demand functions. A relative price increase in coal—e.g. through the introduction of coal taxes—would partly ramp up the consumption of natural gas and crude oil. The effects on CO_2 emissions reductions from lower coal consumption would hence be partly compensated by more emissions from other sources. Nevertheless, since coal products are the most carbon-intensive fossil fuels, our analysis gives the upper bound of possible emissions reductions.

Moreover, in our setting only one country or a group of countries can act as Stackelberg-leader. We consequently neglect policy reactions of other economic decision makers, like retaliation of importing or other exporting countries. Mathematically, representing more than one player at the upper level would constitute an Equilibrium Problem with Equilibrium Constraints (EPEC) which is solved differently; solution methods generally cannot be easily applied to large-scale models.

Finally, the path of the tax rate is exogenously given and not optimally decided on. This modeller's choice reduces complexity and avoids time inconsistencies of large jumps in the tax rate. Moreover, we analyse a variety of possible developments of the tax rate.

5 Conclusions

In this paper we investigate the hypothesis that large coal exporting countries have the option to help achieve global climate change mitigation, and at the same time improve their economic welfare. To this end we construct a tow-level game with a policy optimization problem at the upper level, and an equilibrium model of the international steam coal market at the lower level.

By restricting coal supply to international markets through levying a tax on exports, exporting countries reduce global consumption of coal and can benefit from a terms-of-trade effect and from generated tax revenues. While Australia may unilaterally generate perceivable tax revenues, our results suggest that a coalition of the largest exporters is necessary to significantly lower global CO_2 emissions and achieve welfare improvements. We particularly find a strong rebound effect through increased Chinese coal production for

domestic consumption. Our indicative scenario shows that including an additional coalition member (USA) strongly increases the coalition's total revenue, while the calculated revenue share of the new member is incremental.

International trade law and the possibility of retaliatory trade action by importing countries speak against the introduction of such export taxes and the formation of a cartel. A production-based tax does not incur the same legal obligations under international trade agreements. Results consistently show higher optimal tax levels and higher NPV tax revenues, compared to the respective export tax scenarios. Affecting domestic supply and exports alike, this policy could be hard to justify against the opposition of domestic stakeholders dependent on low-price domestic coal supply. Investigation of why such coal export taxes are not widespread in practice is left for further work.

Without doubt, the analysed export tax alone is insufficient to avoid a severe increase in the global mean temperature. Nevertheless, supply constraints by fossil fuel exporters may hold promise as a climate change mitigation strategy, as they can leave the owners of fossil fuel reserves better off, in contrast to the conventional policy approach of tackling the demand side. This may in turn favour the formation of a global climate agreement.

Future research should investigate the game theoretical properties of coalition formation and its stability and examine the distribution of rents between different stakeholders in a country.

Acknowledgements

We thank Hanna Brauers, Steve Gabriel, Clément Haftendorn, Christian von Hirschhausen, Franziska Holz, Daniel Huppmann, Kai Lessmann, Claudia Kemfert, and Sauleh Siddiqui for helpful discussions and feedback as well as the participants of the IAEE conferences in Düsseldorf 2013, and Rome 2014, and of the Research Seminar on Environment, Resource and Climate Economics in Berlin.

This work is carried out within the research project "RESOURCES: International Resource Markets under Climate Constraints - Strategic Behavior and Carbon Leakage in Coal, Oil and Natural Gas Markets". Funding by the German Ministry of Education and Research (BMBF) within the research framework "Economics of Climate Change" is gratefully acknowledged.

Appendix

A.1 List of Endogenous Variables.

Table A.1: Endogenous Variables

Variable	Description
τ_0^E	Starting value of export tax
τ_0^P	Starting value of production tax
x_{afc}	Quantity sold by producer to consumer
y_{afe}	Quantity sold by producer to exporter
z_{aec}	Quantity sold by exporter to consumer
p_{ac}^C	Price paid by consumer
p_{ae}^E	Price paid by exporter
inv_{af}^P	Investment in production capacity by producer
inv_{afc}^{TC}	Investment in transportation capacity to consumer by producer
inv_{afe}^{TE}	Investment in transportation capacity to exporter by producer
inv_{ae}^E	Investment in export capacity by exporter
mc_{af}^{int}	Intercept of marginal costs of production
α_{af}^P	Dual variable to production capacity constraint
$\alpha_{af}^{inv^P}$	Dual variable to max. investment in production capacity constraint
α_f^{res}	Dual variable to reserve constraint
α_{afc}^{TC}	Dual variable to transport capacity to consumer constraint
α_{afe}^{TE}	Dual variable to transport capacity to exporter constraint
μ_{ae}^E	Dual variable to export capacity constraint
$\mu_{ae}^{inv^E}$	Dual variable to max. investment in export capacity constraint

A.2 Formulation of the Lower Level as Equilibrium Problem

In order to numerically solve the lower level problem described in section 2.2, it needs to be reformulated in terms of KKT conditions, where each condition constitutes the derivative of the Lagrangian of the respective player with respect to one of its decision variables and to each of the dual variables of the constraints. The condition state that in equilibrium the decision variable and dual variables, and the respective derivative are perpendicular to each other.

Producer's KKTs:

$$0 \leq \left(\frac{1}{1+r_f}\right)^{a-1} \Big[- p^C_{ac} + \kappa_f \cdot mc^{int}_{af} + (\kappa_f)^2 \cdot mc^{slp}_f \cdot \left(\sum_c x_{afc} + \sum_e y_{afe} \right) \\ + \kappa_f \cdot trans^{TC}_{fc} + \kappa_f \cdot \alpha^P_{af} + \sum_{a'>a} \kappa_f \cdot \alpha^P_{f,a'} \cdot mc^{int}_f \Big] \\ + 5 \cdot \kappa_f \cdot \alpha^{res}_f + \kappa_f \cdot \alpha^{TC}_{afc} \geq 0 \quad \perp \quad x_{afc} \geq 0 \tag{A.1}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^{a-1} \Big[- p^E_{ae} + \kappa_f \cdot mc^{int}_{af} + (\kappa_f)^2 \cdot mc^{slp}_f \cdot \left(\sum_{c'} x_{afc'} + \sum_{e'} y_{afe'} \right) \\ + \kappa_f \cdot trans^{E}_{fe} + \kappa_f \cdot \alpha^P_{af} + \sum_{a'>a} \kappa_f \cdot \alpha^P_{f,a'} \cdot mc^{int}_f \Big] \\ + 5 \cdot \kappa_f \cdot \alpha^{res}_f + \kappa_f \cdot \alpha^{TE}_{afe} \quad \perp \quad y_{afe} \geq 0 \tag{A.2}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^{a-1} Cinv^P_f - \sum_{a'>a} \alpha^P_{a'f} + \alpha^{inv^P}_{af} \quad \perp \quad inv^P_{af} \geq 0 \tag{A.3}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^{a-1} Cinv^{TC}_{fc} - \sum_{a'>a} \alpha^{TC}_{a'fc} \quad \perp \quad inv^{TC}_{afc} \geq 0 \tag{A.4}$$

$$0 \leq \left(\frac{1}{1+r_f}\right)^{a-1} Cinv^{TE}_{fe} - \sum_{a'>a} \alpha^{TE}_{a'fe} \quad \perp \quad inv^{TE}_{afe} \geq 0 \tag{A.5}$$

$$0 \leq cap^p_f + \sum_{a'<a} \left[inv^P_{a'f} - \left(\sum_c \kappa_f \cdot x_{a'fc} + \sum_e \kappa_f \cdot y_{a'fe} \right) \cdot mc^{int}_f \right] \\ - \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \quad \perp \quad \alpha^P_{af} \geq 0 \tag{A.6}$$

$$0 \leq \overline{inv}^P_f - inv^P_{af} \quad \perp \quad \alpha^{inv^P}_{af} \geq 0 \tag{A.7}$$

$$0 \leq cap^{TC}_{fc} + \sum_{a'<a} inv^{TC}_{a'fc} - \kappa_f x_{afc} \quad \perp \quad \alpha^{TC}_{afc} \geq 0; \tag{A.8}$$

$$0 \leq cap_{fe}^{TE} + \sum_{a'<a} inv_{a'fe}^{TE} - \kappa_f y_{afe} \quad \perp \quad \alpha_{afe}^{TE} \geq 0 \tag{A.9}$$

$$0 \leq res_f - \sum_a \left(\sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \quad \perp \quad \alpha_f^{res} \geq 0; \tag{A.10}$$

$$0 = mc_{af}^{int} - mc_{a-1f}^{int} \cdot \delta_f \cdot \kappa_f \left(\sum_c x_{a-1fc} + \sum_e y_{a-1fe} \right) \quad \perp \quad mc_{af}^{int} \quad \text{(free)} \tag{A.11}$$

Eporter's KKTs

$$0 \leq \left(\frac{1}{1+r_e} \right)^{a-1} \left[-p_{ac}^C + p_{ae}^E + fee_e \cdot \kappa_e + sea_{aec} \cdot \kappa_e + \tau_a^E \right] + \kappa_e \cdot \mu_{ae}^E \quad \perp \quad z_{aec} \geq 0 \tag{A.12}$$

$$0 \leq \left(\frac{1}{1+r_e} \right)^{a-1} \left(Cinv_e^E + \sum_{a'>a} \mu_{a'e}^E + \mu_{ae}^{inv^E} \right) \quad \perp \quad inv_{ae}^E \geq 0 \tag{A.13}$$

$$0 \leq cap_e^E + \sum_{a'<a} inv_{a'e}^E - \left(\sum_c \kappa_e \cdot z_{afe} \right) \quad \perp \quad \mu_{ae}^E \geq 0 \tag{A.14}$$

$$0 \leq \overline{inv}_e^E - inv_{ae}^E \quad \perp \quad \mu_{ae}^{inv^E} \geq 0 \tag{A.15}$$

$$0 \leq China_{ae}^{lic} - \sum_{c' \neq Chn} \kappa_e \cdot z_{aec'} \quad \perp \quad \pi_a^{CHN} \geq 0; \qquad \text{for } e =' CHN' \tag{A.16}$$

Market Clearing – Export and Final Demand:

$$0 = \sum_f y_{afe} - \sum_c z_{aec} \quad \perp \quad p_{ae}^E \quad \text{(free)} \tag{A.17}$$

$$0 = p_{ac}^C - Dint_{ac} - b_{ac} \cdot \left(\sum_f x_{afc} + \sum_e z_{aec} \right) \quad \perp \quad p_{ac}^C \quad \text{(free)} \tag{A.18}$$

A.3 Production Tax – Adjusted Equations

The tax path in Eq. (1) now holds for production tax τ_a^P:

$$\tau_a^P = \tau_0^P \cdot (1 + r_\tau)^{a-a'} \tag{A.19}$$

Accordingly, the optimization problem given by Eq. (2) is adjusted to

$$\max_{\tau_0^P} \sum_{af} \left(\frac{1}{1 + r_g} \right)^{a-1} \cdot \tau_a^P \cdot PROD_{af}, \tag{A.20}$$

where $PROD_{af}$ subsumes the production of all producers f being in the territory of policy maker g are affected by the production tax.

The producer's maximisation problem from Eq. (3) is adjusted by incorporating the tax rate, accordingly.

$$\begin{aligned}
\max_{x_{afc},\, y_{afe},\, inv_{af}^P,\, inv_{afc}^{TC},\, inv_{afe}^{TE}} \Pi_f = \sum_a \left(\frac{1}{1 + r_f} \right)^{a-1} \cdot \Bigg[& \\
\sum_c p_{ac}^C \cdot x_{afc} + \sum_e p_{ae}^E \cdot y_{afe} - Cprod_{af}[x_{afc},\ y_{afe}] & \\
- \left(\sum_c x_{afc} + \sum_e y_{afe} \right) \cdot \tau_a^P & \\
- \sum_c trans_{afc}^C \cdot \kappa_f \cdot x_{afc} - \sum_e trans_{afe}^E \cdot \kappa_f \cdot y_{afe} & \\
- Cinv_{af}^P \cdot inv_{af}^P - \sum_c Cinv_{afc}^{TC} \cdot inv_{afc}^{TC} - \sum_e Cinv_{afc}^{TE} \cdot inv_{afe}^{TE} \Bigg], &
\end{aligned} \tag{A.21}$$

By contrast, the exporter's problem given in Eq. (11) reduces to

$$\begin{aligned}
\max_{z_{aec},\, inv_{ae}^E} \Pi_e = \sum_a \left(\frac{1}{1 + r_e} \right)^{a-1} \cdot \Big[& \sum_c p_{ac}^C \cdot z_{aec} \\
& - \sum_c \left(p_{ae}^E \cdot z_{aec} + fee_e \cdot \kappa_e \cdot z_{aec} + sea_{aec} \cdot \kappa_e \cdot z_{aec} \right) \\
& - Cinv_{ae}^E \cdot inv_{ae}^e \Big].
\end{aligned} \tag{A.22}$$

A.4 Solution Algorithm Using NLPEC and a Disjunctive Constraints Formulation

The Disjunctive Constraints formulation is an established method to solve MPECs, where the complementarity conditions of the lower level are reformulated into a MIP. However, this technique has two drawbacks well discussed in the literature: for large models the method is computationally expensive (cf. Luo et al., 1996), while at the same time it requires the definition of upper bounds for all endogenous variables. Results are highly sensitive to these bounds and a 'bad choice' can generate misleading results and infeasibilities (cf. Gabriel and Leuthold, 2010).[19]

We develop an algorithm that combines NLPEC and Disjunctive Constraints solution techniques to overcome the drawbacks of the individual methods. Figure A.1 depicts how the two alternative formulations are combined in our approach.

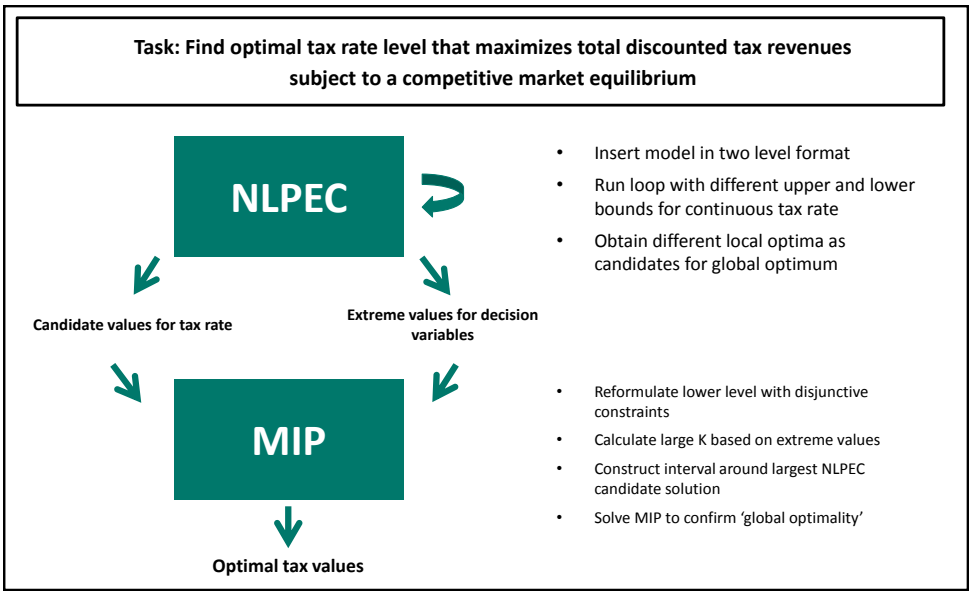


Figure A.1: Illustration of MPEC solution strategy.

A.4.1 First Step: GAMS NLPEC Solver

In a first step, which is similar to the approach described in section 2.3, we solve the model using the NLPEC solver. In order to obtain different local optima as candidates for the global optimum, we vary the upper and lower bound of decision variable τ_0^e. Furthermore,

[19] Another method proposed by Siddiqui and Gabriel (2013) uses Schur's decomposition and variables of specially ordered sets (SOS-Type 1 variables) to avoid exogenously choosing suitable (upper) bounds.

extreme values for all variables are reported and stored for further use in the second step. To this end the model is defined by the upper-level objective function Eq. (2) together with the lower level being formulated by means of KKT conditions, Eqs. (A.1-A.18).

A.4.2 Second Step: Disjunctive Constraint Reformulation

In a second step, we test the candidate NLPEC solution, which has the highest upper-level objective value, for optimality by formulating a linear MIP. For this purpose the upper and lower level needs to be linearised, and the complementarity conditions, i.e. the duality between equation and respective variable, need to be replaced by disjunctive constraints. Both a binary variable bin, and a sufficiently large positive constant K have to be defined for each complementarity condition.

For instance, focussing on the exporter's optimization problem we can write complementarity condition Eq. (A.12) by means of disjunctive constraints as follows:

$$0 \leq \left(\frac{1}{1+r_e}\right)^{a-1} \Big[-p^C_{ac} + p^E_{ae} + fee_e \cdot \kappa_e + sea_{aec} \cdot \kappa_e + \tau^E_a \Big] + \kappa_e \cdot \mu^E_{ae} \leq bin^z_{aec} \cdot K^z_{aec} \tag{A.23}$$

$$0 \leq z_{aec} \leq (1 - bin^z_{aec}) \cdot K^z_{aec}. \tag{A.24}$$

Furthermore, the objective function at the upper level, more specifically the bilinear term given by the product of tax rate and exported quantities, has to be linearised. We follow Gabriel and Leuthold (2010) in discretising the decision variable to $\tau^e_{0,d}$, where index d denotes predetermined discrete options for the export tax. Each potential tax rate is related to a binary variable bin^τ_d and a sufficiently large positive constant K^τ_d. In essence, the algorithms determines the highest objective value by choosing one of the given tax rates, i.e. by setting the corresponding binary variable to unity. The linearised upper level

expressed by disjunctive constraints reads as follows

$$obj = max \sum_{d} rev_d \tag{A.25}$$

$$rev_d \leq \sum_{aec'} \left(\frac{1}{1+r_g} \right)^{a-a'} \left[\tau^E_{0d} \cdot (1+r_\tau)^{a-a'} EXP_{aec'} \right] \tag{A.26}$$

$$\sum_{d} bin^\tau_d = 1 \tag{A.27}$$

$$rev_d \leq K^\tau_d \cdot bin^\tau_d. \tag{A.28}$$

While Eq. (A.25) maximises the sum of potential tax revenues rev_d over all possible discrete choices, Eq. (A.26) links these revenues to the different tax rate options. By Eq. (A.27) it is guaranteed that only one tax options is chosen, while Eq. (A.28) only allows the corresponding tax revenue to this tax rate to be positive. This ensures that Eq. (A.25) ultimately chooses the highest possible tax revenue.

In order to test the candidate solution provided by NLPEC, we define the set of exogenous export tax rates in a close range around it. We hence test for optimality in a constrained set of choices.[20]

[20] In GAMS we use the solver CPLEX, initialize a starting value (option MIPSTART = 1) and use more than one CPU cores for calculation (option threads > 1).

A.5 Model Specification

Table A.2: Consumer, producer and exporter nodes in COALMOD-World.
Source: Holz et al. (2015)

Country	Producers	Region	Exporters	Port	Consumers	Region
Canada	*P_CAN*				*C_CAN*	Ontario
	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
	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
USA	*P_USA_ILL*	Illinois Basin	*E_USA_W*	Portland, OR	*C_USA_SC*	AR, LA, OK, TX
	P_USA_APP	Appalachian			*C_USA_SE*	AL, DE, DC, FL, GA, KY, MD, MS, NC, SC, TN, VA, WV
					C_USA_NE	CT, ME, MA, NH, NJ, NY, PA, RI, VT
Colombia	*P_COL*		*E_COL*	Cartagena		
Venezuela	*P_VEN*		*E_VEN*	Puerto la Cruz		
Morocco					*C_MAR*	
Portugal					*C_PRT*	
Spain					*C_ESP*	
UK					*C_GBR*	
Netherlands/ France/Belgium					*C_NFB*	Netherlands, France, Belgium
Germany					*C_DEU*	
Denmark					*C_DNK*	
Finland					*C_FIN*	
Italy					*C_ITA*	
Poland	*P_POL*		*E_POL*	Gdansk	*C_POL*	
Turkey					*C_TUR*	
Israel					*C_ISR*	
Ukraine	*P_UKR*	Ukrainian/Russian Donetsk	*E_Black_Sea_UKR*	Odessa	*C_UKR*	
Kazakhstan	*P_KAZ*	Ekibastuz	*E_RUS_West*	Ust?Luga	*C_KAZ*	
Russia	*P_RUS*	Kemerovo/Kuznets	*E_RUS_East*	Vladivostok	*C_RUS_Central*	
			E_Black_Sea_RUS	Odessa	*C_RUS_Siberia*	
South Africa	*P_ZAF*		*E_ZAF*	Richards Bay	*C_ZAF*	
India	*P_IND_North*	Jharkhand, Madhya Pradesh, Chhattisgarh, West Bengal			*C_IND_East*	Bihar, Chhatisgarh, Jharkhand, Orissa, West Bengal
	P_IND_Orissa	Orissa			*C_IND_North*	Delhi, Punjab, Rajasthan, Uttar Pradesh
	P_IND_West	Maharashtra			*C_IND_West*	Gujarat, Madhya Pradesh, Maharashtra
	P_IND_South	Andhra Pradesh			*C_IND_South*	Andhra Pradesh, Karnataka, Tamil Nadu
Thailand					*C_THA*	
Malaysia					*C_MYS*	
Vietnam	*P_VNM*					
Indonesia	*P_IDN*		*E_IDN*	Surabaya	*C_IDN*	
China	*P_CHN_SIS*	Gansu, Inner Mongolia, Hebei, Ningxia, Shaanxi, Shaaxi, Shanxi	*E_CHN*	Qinhuangdao	*C_CHN_Northeast*	Heilongjiang, Jilin, Liaoning
	P_CHN_Northeast	Heilongjiang, Jilin, Liaoning, Tianjin			*C_CHN_Main*	Beijing, Tianjin, Hebei, Henan, Shandong, Tianjin
	P_CHN_HSA	Anhui, Bejing, Fujian, Henan, Jiangsu, Jiangxi, Shandong, Zhejiang			*C_CHN_Eastern*	Anhui, Jiangsu, Hubei, Shanghai, Zhejiang
	P_CHN_YG	Chongqing, Guangxi, Guizhou, Guizhou, Hubei, Hunan, Sichuan, Yunnan			*C_CHN_South*	Chongqing, Fujian, Guangdong, Guangxi, Guizhou, Hong Kong, Hunan, Jiangxi, Sichuan
					C_CHN_SIS	Shanxi, Shaaxi, Inner Mongolia
Korea					*C_KOR*	
Japan					*C_JPN*	
Taiwan					*C_TWN*	
Philippines					*C_PHL*	
Australia	*P_AUS_QLD*	Queensland	*E_AUS_QLD*	Gladstone	*C_AUS*	
	P_AUS_NSW	New South Wales	*E_AUS_NSW*	Botany Bay		
Mozambique	*P_MOZ*		*E_MOZ*	Maputo		
Mongolia	*P_MNG*					

A.6 *Base Case* results

Table A.3: Consumption, domestic supply, and imports by consuming country in the *Base Case* in 2010, 2020, and 2030, in Mt.

	2010		2020		2030	
	Import-Export	Domestic Supply	Import-Export	Domestic Supply	Import-Export	Domestic Supply
Australia	-92	63	-125	61	-135	51
Canada	9	0	9	0	8	0
China*	93	2388	414	2666	535	2536
Colombia	-60	0	-112	0	-136	0
Denmark	4	0	3	0	3	0
Finland	5	0	4	0	3	0
Germany	31	0	26	0	19	0
India	64	488	208	628	322	747
Indonesia	-270	58	-370	81	-399	90
Israel	9	0	8	0	6	0
Italy	14	0	13	0	9	0
Japan	124	0	130	0	126	0
Kazakhstan	-30	61	-33	60	-28	58
Korea	83	0	75	0	63	0
Malaysia	21	0	29	0	32	0
Morocco	4	0	5	0	6	0
Mongolia	-17	0	-52	0	-56	0
Mozambique	-4	0	-12	0	0	0
Philippines	11	0	13	0	15	0
Poland	0	71	0	62	-5	45
Portugal	4	0	4	0	3	0
Russia	-40	69	-83	72	-88	82
South Africa	-72	187	-104	231	-126	231
Spain	10	0	8	0	6	0
Taiwan	62	0	75	0	79	0
Thailand	17	0	20	0	22	0
The Netherlands, France, Belgium	22	0	18	0	14	0
Turkey	16	0	16	0	15	0
Ukraine	4	19	-5	7	-5	6
United Kingdom	20	0	16	0	12	0
USA	-19	886	-184	859	-303	793
Venezuela	-5	0	-14	0	-17	0
Vietnam	-18	0	0	0	0	0

*net with 20 Mt exports to Taiwan in 2010

A.7 Global Trade Flows in 2030 by Case

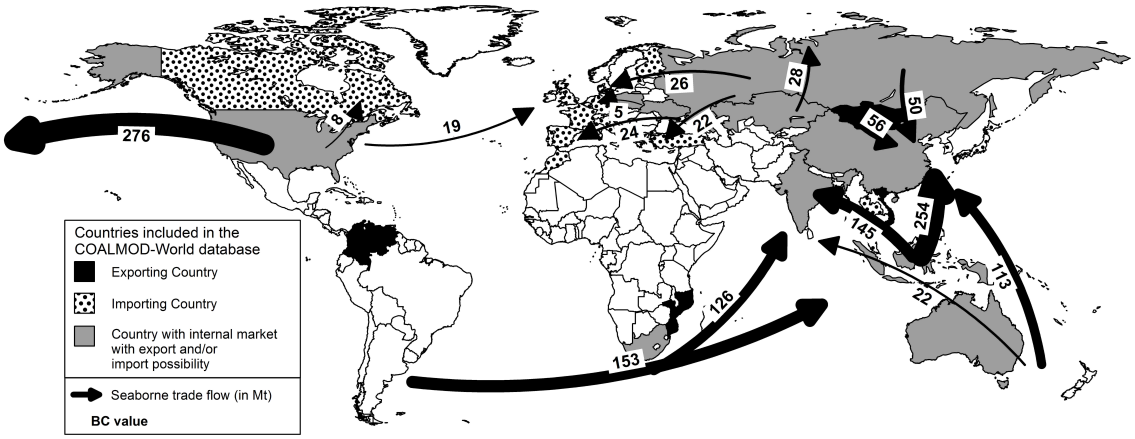


Figure A.2: Global trade flows in the *Base Case* in 2030, in Mt.

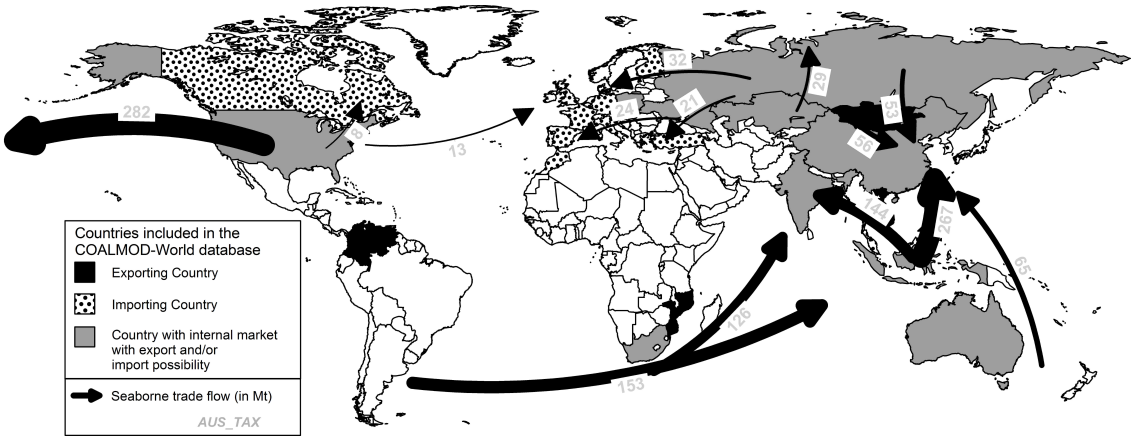


Figure A.3: Global trade flows in *Tax AUS* in 2030, in Mt.

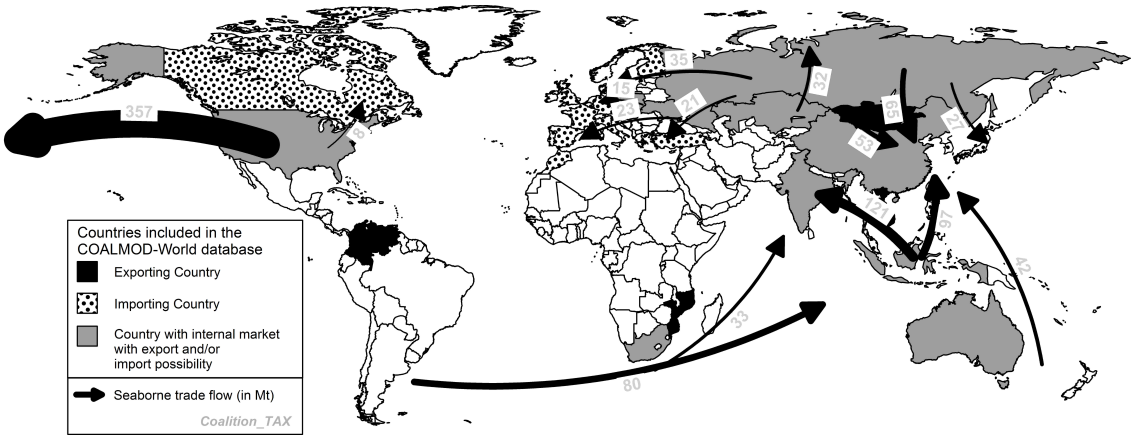


Figure A.4: Global trade flows in *Tax Coalition* in 2030, in Mt.

References

Asheim, Geir B. (2013) 'A distributional argument for supply-side climate policies.' *Environmental and Resource Economics* 56(2), 239–254

Bohm, Peter (1993) 'Incomplete international cooperation to reduce CO_2 emissions: Alternative policies.' *Journal of Environmental Economics and Management* 24(3), 258–271

Böhringer, Christoph, Knut Einar Rosendahl, and Jan Schneider (2014) 'Unilateral climate policy: Can OPEC resolve the leakage probem?' *The Energy Journal* 35(4), 79–100

Brander, James A., and Barbara J. Spencer (1985) 'Export subsidies and international market share rivalry.' *Journal of International Economics* 18(1-2), 83–100

Burniaux, Jean-Marc, and Joaquim Oliveira Martins (2012) 'Carbon leakages: A general equilibrium view.' *Economic Theory* 49(2), 473–495

Eisenack, Klaus, Ottmar Edenhofer, and Matthias Kalkuhl (2012) 'Resource rents: The effects of energy taxes and quantity instruments for climate protection.' *Energy Policy* 48, 159–166

Fæhn, Taran, Cathrine Hagem, Lars Lindholt, Ståle Mæland, and Knut Einar Rosendahl (2014) 'Climate policies in a fossil fuel producing country - demand versus supply side policies.' CESifo Working Paper No. 5105

Fortuny-Amat, J., and B. McCarl (1981) 'A representation and economic interpretation of a two-level programming problem.' *The Journal of the Operational Research Society* 32(9), 783–792

Gabriel, Steven A., and Florian U. Leuthold (2010) 'Solving discretely-constrained MPEC problems with applications in electric power markets.' *Energy Economics* 32(1), 3–14

Haftendorn, Clemens, and Franziska Holz (2010) 'Modeling and analysis of the international steam coal trade.' *The Energy Journal* 31(4), 205–229

Haftendorn, Clemens, Claudia Kemfert, and Franziska Holz (2012a) 'What about coal? Interactions between climate policies and the global steam coal market until 2030.' *Energy Policy* 48, 274–283

Haftendorn, Clemens, Franziska Holz, and Christian von Hirschhausen (2012b) 'The end of cheap coal? A techno-economic analysis until 2030 using the COALMOD-World Model.' *Fuel* 102, 305–325

Harstad, Bard (2012) 'Buy coal! A case for supply-side environmental policy.' *Journal of Political Economy* 120(1), 77–115

Hoel, Michael (1994) 'Efficient climate policy in the presence of free riders.' *Journal of Environmental Economics and Management* 27(3), 259–274

_ (2013) 'Supply side climate policy and the green paradox.' CREE Working Paper 2/2013

Holz, Franziska, Clemens Haftendorn, Roman Mendelevitch, and Christian von Hirschhausen (2015) 'The COALMOD-World Model: World coal markets through 2030.' In *Resurgent Coal: Production, Transport, and Use of the World's Fastest-Growing Energy Source,* ed. Richard K. Morse and Mark C. Thurber (Cambridge, UK: Cambridge University Press)

Huppmann, Daniel, and Franziska Holz (2012) 'Crude oil market power—a shift in recent years?' *The Energy Journal* 33(4), 1944–9089

IEA, International Energy Agency (2012) 'World Energy Outlook 2012.' OECD/IEA. Paris

_ (2013) 'Coal Information 2013.' OECD/IEA. Paris

Johansson, Daniel J.A., Christian Azar, Kristian Lindgren, and Tobias A. Persson (2009) 'OPEC strategies and oil rent in a climate conscious world.' *The Energy Journal* 30(3), 23–50

Kalkuhl, Matthias, and Robert J. Brecha (2013) 'The carbon rent economics of climate policy.' *Energy Economics* 39, 89–99

Kolstad, Charles D., and David S. Abbey (1984) 'The effect of market conduct on international steam coal trade.' *European Economic Review* 24(1), 39–59

Kolstad, Charles D., and Jr. Wolak, Frank A. (1985) 'Strategy and market structure in western coal taxation.' *The Review of Economics and Statistics* 67(2), 239–249

Liski, Matti, and Olli Tahvonen (2004) 'Can carbon tax eat OPEC's rents?' *Journal of Environmental Economics and Management* 47(1), 1–12

Luo, Zhi-Quan, Jong-Shi Pang, and Daniel Ralph (1996) *Mathematical Programs with Equilibrium Constraints.* Cambridge University Press. Cambridge, UK

McGlade, Christophe, and Paul Ekins (2015) 'The geographical distribution of fossil fuels unused when limiting global warming to 2°c.' *Nature* 517, 187–190

Meinshausen, Malte, Nicolai Meinshausen, William Hare, Sarah C. B. Raper, Katja Frieler, Reto Knutti, David J. Frame, and Myles R. Allen (2009) 'Greenhouse-gas emission targets for limiting global warming to 2°c.' *Nature* 458(7242), 1158–1162

Paulus, Moritz, and Johannes Trüby (2011) 'Coal lumps vs. electrons: How do chinese bulk energy transport decisions affect the global steam coal market?' *Energy Economics* 33(6), 1127–1137

Persson, Tobias A., Christian Azar, Daniel J.A. Johansson, and Kristian Lindgren (2007) 'Major oil exporters may profit rather than lose, in a carbon-constrained world.' *Energy Policy* 35(12), 6346–6353

PwC (2014) 'Mining in Indonesia 2014.' Technical Report, PricewaterhouseCoopers International Limited

Rogner, H.-H., R. F. Aguilera, C. Archer, R. Bertani, S. C. Bhattacharya, M. B. Dusseault, L. Gagnon, H. Haberl, M. Hoogwijk, A. Johnson, M. L. Rogner, H. Wagner, and

V. Yakushev (2012) 'Energy resources and potentials.' In 'Global Energy Assessment - Toward a Sustainable Future.' Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, Chapter 7, 423-512

Schernikau, Lars (2010) *Economics of the International Coal Trade: The Renaissance of Steam Coal* (Springer)

Siddiqui, Sauleh (2011) *Solving Two-Level Optimization Problems with Applications to Robust Design and Energy Markets.* Dissertation. University of Maryland

Siddiqui, Sauleh, and Steven A. Gabriel (2013) 'An SOS1-based approach for solving MPECs with a natural gas market application.' *Networks and Spatial Economics* 13(2), 205–227

Sinn, Hans Werner (2008) 'Public policies against global warming: A supply side approach.' *International Tax and Public Finance* 15(4), 360–394

Trüby, Johannes (2013) 'Strategic behaviour in international metallurgical coal markets.' *Energy Economics* 36, 147–157

Trüby, Johannes, and Moritz Paulus (2012) 'Market structure scenarios in international steam coal trade.' *The Energy Journal* 33(3), 91–123