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

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

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## 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<sub>2</sub> 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<sub>2</sub> emissions from steam coal by up to 200 Mt CO<sub>2e</sub> per year. Comparable production-based tax scenarios consistently yield higher tax revenues but may be hard to implement against the opposition of disproportionately 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)

# 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<sup>1</sup> levied by Australia, the world's second largest steam coal exporter, or alternatively by a group of major exporters.<sup>2</sup> We

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<sup>1</sup>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.

<sup>2</sup>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. For Indonesia, see for instance <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)

analyse the short-term and long-term effects on tax revenues, CO<sub>2</sub> 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: Besides coining the term *Green Paradox*, he proposes a subsidy scheme to incentivise the conservation of carbon in the ground as a climate policy instrument. [Harstad \(2012\)](#), in turn, 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.<sup>3</sup>

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.

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<sup>3</sup>[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 (Green Paradox).

[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.

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.<sup>4</sup> 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. 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 (cf. [IEA, 2013](#); [Trüby and Paulus, 2012](#); [Haftendorn and Holz, 2010](#)) and represent the international steam coal market as being competitive. We further assume that national authorities of major exporting countries may well exert an influence

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<sup>4</sup>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](#)).

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.

Following [Tahvonen \(1995\)](#), [Liski and Tahvonen \(2004\)](#) 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. \(2010\)](#) 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 the resource-rich Norway. While focusing on the crude oil market, they find that the largest contribution to meet CO<sub>2</sub> 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<sub>2</sub> 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, which can increase their domestic supply to a certain extent.

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<sub>2</sub> 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 US and find a substantial increase in NPV revenue while the county’s calculated revenue share is marginal.

Our results show that changing from a 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 against 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

Consider a two-stage game with an optimal policy problem at the upper, and an equilibrium model of the international steam coal market at the lower level. While the economic decision maker  $g$  anticipates the equilibrium reactions of all market participants, these economic players—namely producers  $f \in F$ , exporters  $e \in E$  and final consumers  $c \in C$  of steam coal—take the policy decision parametrically.<sup>5</sup>

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<sup>5</sup>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](#)).



## 2.1 Upper Level: Policy Maker as Stackelberg-Leader

At the upper level, policy maker  $g$  can levy a tax  $\tau_a^e$  on steam coal exports in periods  $a \in A$  in order to maximise the NPV of tax revenues from all future periods. While the policy maker can decide on the initial tax rate  $\tau_0^e$  starting in period  $a = a'$ , the path is predetermined by an annual growth rate of  $r_\tau$ .<sup>6</sup>

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

We model the export tax based on the energy content of exported volumes; it is hence proportional to a carbon tax.<sup>7</sup> The optimization problem is given by

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

where  $EXP_{aec'}$  subsumes total exports of all exporters  $e$  being located in decision maker  $g$ 's territory, with consumption nodes  $c'$  being not. Periodic revenues are discounted at rate  $r_g$ .

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<sup>6</sup>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. On 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.

<sup>7</sup>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.<sup>8</sup> 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, the capacity is increased and can operate as of 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—a *mine mortality mechanism*.

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<sup>8</sup>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 below). 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](#).

### 2.2.1 A Producer's Problem

Producer  $f$  is characterized by the quality  $\kappa_f$  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  $r_f$ . Accordingly,

$$\begin{aligned} \max_{x_{afc}, y_{afe}, inv_{af}^P, inv_{afc}^{TC}, inv_{afe}^{TE}} \Pi_f = \sum_a \left( \frac{1}{1+r_f} \right)^{a-1} \cdot \left[ \right. & (3) \\ \sum_c p_{ac} \cdot x_{afc} + \sum_e p_{ae} \cdot y_{afe} - C_{prod_{af}}[x_{afc}, y_{afe}] & \\ - \sum_c trans_{afc}^C \cdot \kappa_f \cdot x_{afc} - \sum_e trans_{afe}^E \cdot \kappa_f \cdot y_{afe} & \\ - C_{inv_{af}^P} \cdot inv_{af}^P - \sum_c C_{inv_{afc}^{TC}} \cdot inv_{afc}^{TC} - \sum_e C_{inv_{afe}^{TE}} \cdot inv_{afe}^{TE} & \left. \right], \end{aligned}$$

with revenues being generated from selling coal to local consumers,  $x_{afc}$  at price  $p_{ac}$  and to exporters  $y_{afe}$  at price  $p_{ae}$ . The remaining terms of Eq. (3) depict the costs of production, the costs of transportation to the respective buyers and the costs of potential investments into expanding the capacity of production and transportation to consumers and ports. 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  $\kappa_f$ , which reflects the producer-specific conversion rate.

We assume a production cost function  $C_{prod_{af}}$  that is quadratic in extracted quantities

leading to linear periodic marginal costs of extraction:

$$MC_{af} = mc_{af}^{int} + mc_f^{slp} \cdot \left( \sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right), \quad (4)$$

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

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

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

Producer  $f$  then maximizes its objective function with respect to quantities sold to consumers  $x_{afc}$  and exporters  $y_{afe}$ , as well as by deciding on investments in expanding the capacity of production  $inv_{af}^P$  and the capacity of transportation to consumers,  $inv_{afc}^{TC}$  and ports  $inv_{afe}^{TE}$ . The optimisation problem is subject to five constraints:<sup>9</sup>

The first constraint 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

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<sup>9</sup>For each constraint, the respective dual variable, i.e. Langrangian multiplier, is given in parentheses.

mines,

$$\begin{aligned} cap_f^P + \sum_{a' < a} \left[ inv_{a'f}^P - \left( \sum_c \kappa_f \cdot x_{a'fc} + \sum_e \kappa_f \cdot y_{a'fe} \right) \cdot mc\_int\_var_f \right] \geq \\ \sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \quad (\alpha_{af}^P). \end{aligned} \quad (6)$$

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

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

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

Fourth, cumulative extraction over the whole model horizon must not exceed available reserves,

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

and finally, periodic investments in capacity expansions are limited according to

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

### 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 in period  $a$ :  $inv_{ae}^E$ . Accordingly,

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

Exports  $z_{aec}$  are sold at price  $p_{ac}$  to consumer  $c$ , whereas costs incur from purchasing the coal at price  $p_{ae}$ , 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  $\kappa_e$ . In addition, the export tax has to be paid, if exporter  $e$  is located in the territory of decision maker  $g$ . Finally, investments in export capacity,  $inv_{ae}^E$  can be made at per unit expansion costs of  $Cinv_{ae}^E$ .

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

$$cap_e^E + \sum_{a < a'} inv_{a'e}^E \geq \sum_c \kappa_e \cdot z_{aec} \quad (\mu_{ae}^E), \quad (12)$$

and a maximum periodic investment level to expand this export capacity

$$inv_{ae}^E \leq \overline{inv}_{ae}^E \quad (\mu_{ae}^{inv^E}). \quad (13)$$

Parameter  $cap_e^E$  denotes the initial export capacity, while  $\overline{inv}_{ae}^E$  determines the maximum periodic investment possibilities of exporter  $e$ . Again, the dual variables to these constraints (i.e.  $\mu_{ae}^E$  and  $\mu_{ae}^{inv^E}$ ) are given in parentheses.

### 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

$$\sum_f y_{afe} = \sum_c z_{aec} \quad (p_{ae}) \quad (14)$$

$$p_{ac}^c = int_{ac}^D + b_{ac} \cdot \left( \sum_f x_{afc} + \sum_e z_{aec} \right). \quad (15)$$

## 2.3 Solution Algorithm

From a mathematical perspective the two-level problem described above, Eqs. (1)-(15), is a Mathematical Program under Equilibrium Constraints (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.<sup>10</sup>

The most readily available option to solve MPECs using the software GAMS is to rely on the commercial solver NLPEC. NLPEC reformulates the specified MPEC; it works

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<sup>10</sup>See [Luo et al. \(1996\)](#) who provide an overview of different solution techniques for MPECs which has been updated by [Siddiqui \(2011\)](#).

computationally fast and has been recently applied in the literature (cf. [Huppmann and Holz, 2012](#); [Trüby, 2013](#)). However, it is opaque and does not necessarily provide the user with the globally optimal solution.

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). 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](#)).<sup>11</sup>

We develop an algorithm that combines these two solution techniques:<sup>12</sup> In a first step, we solve the model formulated as equilibrium problem using the NLPEC solver. In order to obtain different local optima as candidate solutions, we vary the upper and lower bounds of decision variable  $\tau_0^e$  in a multitude of runs. In a second step, we test the candidate NLPEC solution with the highest upper-level objective value for optimality by means of a linear MIP formulation. We discretise the upper level optimization problem by choosing a set of exogenous export tax rates around the NLPEC candidate solution and reformulate the equilibrium using disjunctive constraints. We hence test for optimality in a constraint set of choices.

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<sup>11</sup>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. Furthermore, [Steffensen and Ulbrich \(2010\)](#) present a relaxation scheme to the complementarity constraints and examine efficiency and robustness of their approach.

<sup>12</sup>A detailed presentation of our algorithm is deferred to the Appendix [A.3](#).



### 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.<sup>13</sup>

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.

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.<sup>14</sup>

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<sup>13</sup>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.

<sup>14</sup>Reference consumption levels, reference prices and demand price elasticities are used to derive the linearly approximated inverse demand curve in Eq. (15).

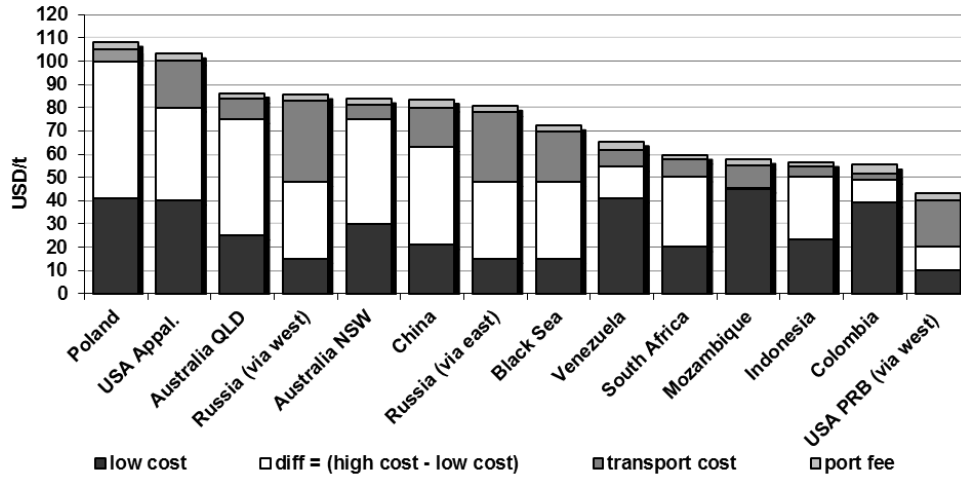


Figure 1: FOB costs in 2010 for export countries in COALMOD-World, in USD/t.

Source: Holz et al. (2015)

The NPS is a scenario of moderate climate policy, assuming the implementation of current energy and climate policy initiatives. While CO<sub>2</sub> 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.<sup>15</sup> Australia has a large share in international trade of steam coal

<sup>15</sup>We distinguish the two Australian coal producing regions New South Wales and Queensland. The same tax rate applies to both regions.

(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

We expect the implementation of an export tax on coal to lead to four partial effects. First, coal extraction and exports from the tax-implementing country (or group of countries) 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. On the one hand, export competitors compensate for the lower international supply. On the other hand, 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 is reduced. These effects translate into a change in the patterns of trade while global CO<sub>2</sub> emissions are reduced.

The analyses of the following cases will particularly focus on these tax-induced changes in the patterns of consumption, production and trade.<sup>16</sup>

#### 4.1 Scenario 1: A Unilateral Australian Export Tax

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 equivalent to a carbon tax of 6.7 USD/tCO<sub>2</sub>, or a tax of about 18 USD per tonne of Australian steam coal.

Figure 2 shows that periodic tax revenues stays more or less constant between 2015 and 2030, with a bump in 2020. Given a discount rate of 2.5%, the linearly approximated NPV of tax revenues until 2030 is around 16 bn. USD.

Australian consumption, production and exported quantities are affected by its tax on exports (see Figure 3). In the *Base Case*, Australian exports increase over time by almost 50% between 2010 and 2030. In *Tax AUS*, however, in every period they are significantly lower than in the *Base Case*, e.g. by around 50% in 2030. Due to the tax introduction in 2015, exports decrease from their 2010 level until 2020, before they

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<sup>16</sup>Guiding *Base Case* results can be found in Table A.3 in the Appendix.

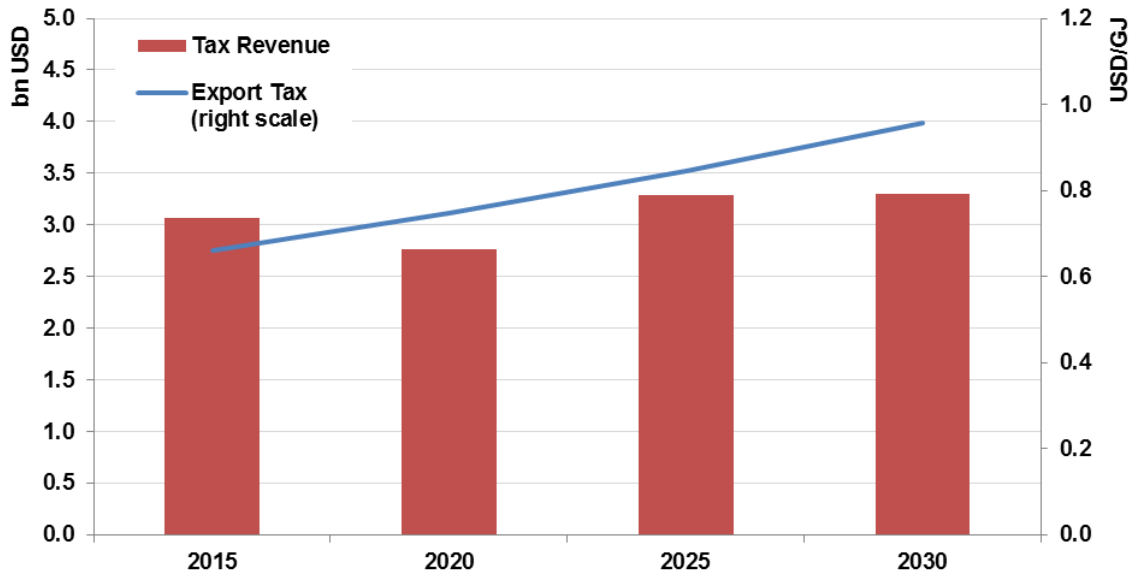


Figure 2: Australian export tax, in USD/GJ, and tax revenues, in bn. USD, over time.

remain nearly constant for the remaining model years.

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*. In this case, consumption levels are higher; though only to a small extent, namely up to 14% above the *Base Case* value in 2030.

The effect on Australian consumption is small compared to the export effect, therefore production levels are shifted almost by the same amount as export levels. The gap between *Base Case* production level and those of *Tax AUS* increase from 39 Mt in 2015 to 62 Mt in 2030. Australian consumer prices are well below the *Base Case* in *Tax AUS*. In each period this price difference is smaller than the tax rate, though.

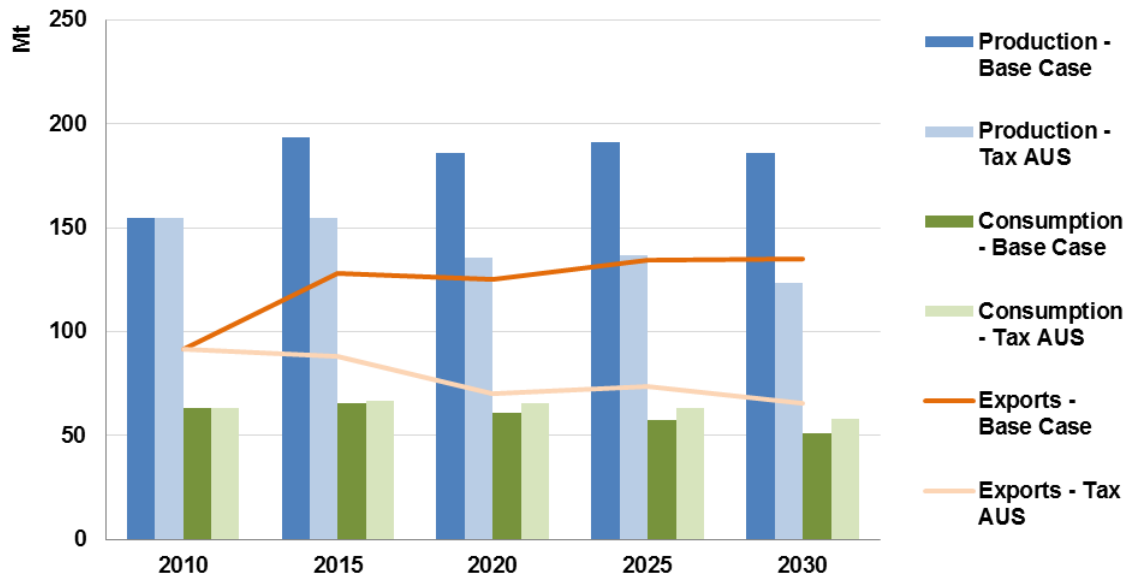


Figure 3: Australian production, consumption and exports in the *Base Case* and in *Tax AUS*, in Mt.

The reaction to an Australian export tax is particularly visible in the production levels of all other countries (RoW). See Figure 4 for a detailed depiction of production reactions.

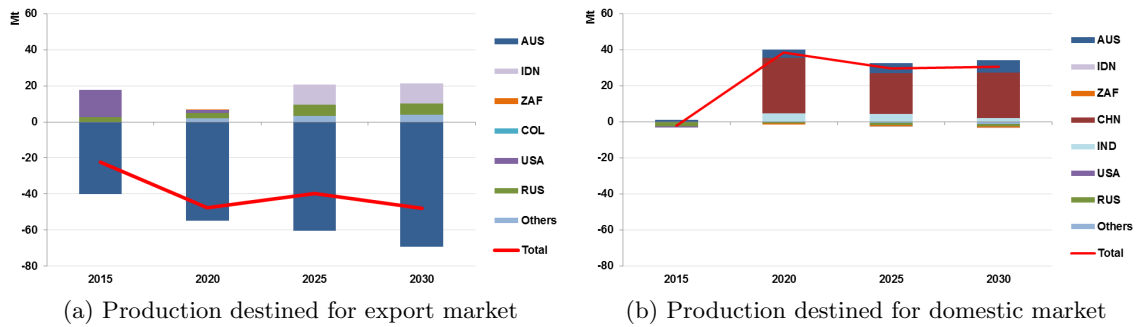


Figure 4: Changes in global production relative to the *Base Case*, by destination, in Mt.

When the tax is first introduced in 2015, the exporting competitors are not able to rapidly expand their exports as they are already running at capacity, with the exemption of some supply from Russia which is redirected from its domestic market, and more sig-

nificantly from the US. At the same time the large consumers, namely China and India, are not able to increase their domestic production. It is only by 2020, then their domestic producers can expand production capacity, and due to high import prices and sufficient domestic transport capacity, gain a comparative advantage over high-price imports.

After 2020, international export competitors of Australia increase their exported volumes. After 2025, the USA is substituted by Indonesia which together with Russia compensates for around 25% of reduced Australian exports, while, interestingly, 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 reduced relative to the *Base Case*.

In sum, global production is reduced, but 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 the later periods reduced exports are compensated by domestic production and, to a smaller extend, by other exporters.

Global consumption patterns are changed in different countries for different reasons (see Figure 5). 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. There is an increasing pressure to shift supply from the domestic to the export market.

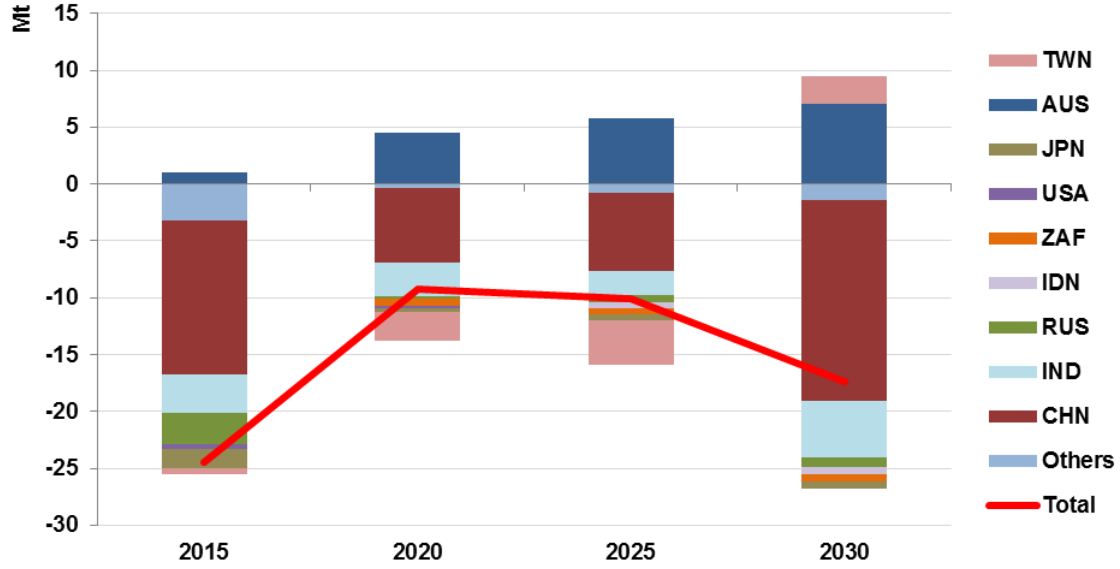


Figure 5: Changes in patterns of global consumption relative to the *Base Case*, in Mt.

In line with consumption, global CO<sub>2</sub> emissions are lower than in the *Base Case*. Yearly emissions are 63 Mt CO<sub>2e</sub> lower in 2015 which corresponds to 28% of GHG emissions from the Australian energy sector in the 2012.<sup>17</sup> This amount drops to 27 Mt CO<sub>2e</sub> in 2020 but rises to 51 Mt CO<sub>2e</sub> in 2030, again. Given the optimal tax level, emissions from Australian coal drop by on average 150 Mt CO<sub>2e</sub>. Compared to average emissions from Australian coal of 558 Mt CO<sub>2e</sub>, this is a significant reduction. Note that consumption-based emissions increase in Australia but global emissions decrease in line with global coal consumption.

Figure 6 summarizes the impact of an Australian export tax decomposed into exports

<sup>17</sup>See <http://ageis.climatechange.gov.au/>.



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 is observable. <sup>18</sup> 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.

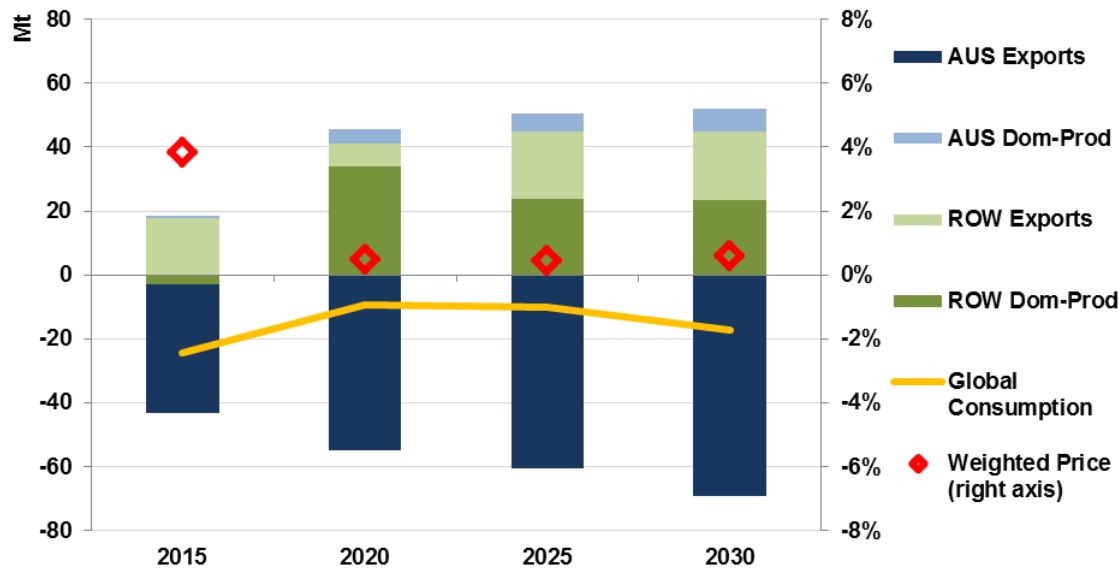


Figure 6: Decomposed impact of an Australian export tax relative to the *Base Case*, in Mt, and change in weighted CIF prices in %.

<sup>18</sup>In the Appendix, global steam coal trade flows for all three analyzed cases are supplementary depicted for the year 2030.

#### 4.1.1 Robustness Checks

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<sub>2</sub> compared to the 6.73 USD/tCO<sub>2</sub> with the default assumption of a 5% discount rate.

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 7). Among the tested growth parameters, the default setting leads to a slightly lower NPV of tax revenues.

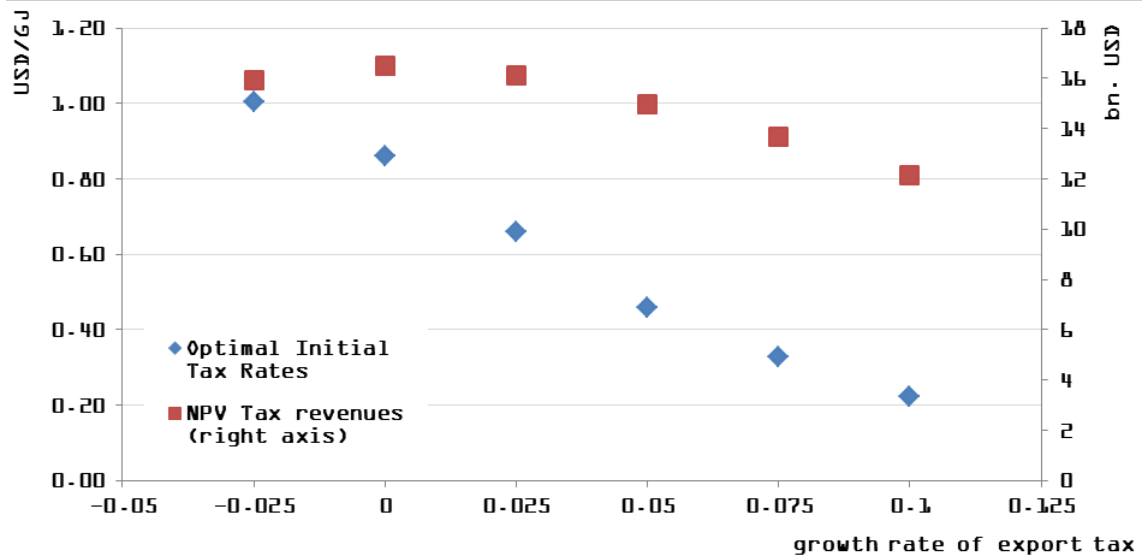


Figure 7: Optimal initial tax rates, in USD/GJ and NPV of tax revenues, in bn. USD, as a function of the growth rate of the export tax, in % per annum.

#### 4.1.2 Export vs. Production Tax

The analysed case of an Australian export tax leads to a positive net effect on global CO<sub>2</sub> emissions. However, coal consumption is shifted to domestic consumption and Australian emissions necessarily 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.<sup>19</sup>

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 8 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<sub>2</sub>. Emission reductions are more pronounced as both Australian exports and consumption decline.

The global optima, however, is reached at a much higher initial tax level of almost 40 USD/tCO<sub>2</sub>. Tax revenue is substantially higher; emissions reduced to a larger extent. By contrast, we can see from Figure 8 that welfare (producer surplus + consumer surplus + tax revenue) is substantially reduced and from Figure 9 that the production tax rate is prohibitive for any profitable exports. Only domestic consumption is taxed at the optimum. Up to the maximum the increase in the tax rate is stronger than the decline in quantities.<sup>20</sup> Production in 2030 is reduced to a tenth compared to the *Base Case*.

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<sup>19</sup>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.7.

<sup>20</sup>Note that these results are driven by our assumptions on demand price elasticities and by linearly approximating 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.

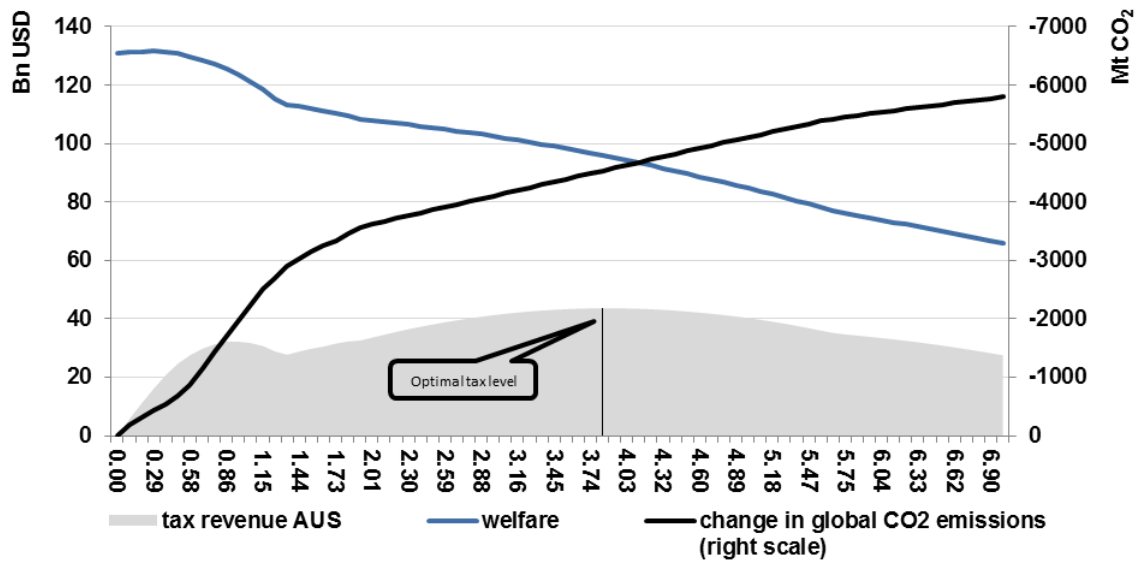


Figure 8: Australian tax revenues, welfare and the reduction in CO<sub>2</sub> emission as a function of the initial production tax rate, in USD/GJ.

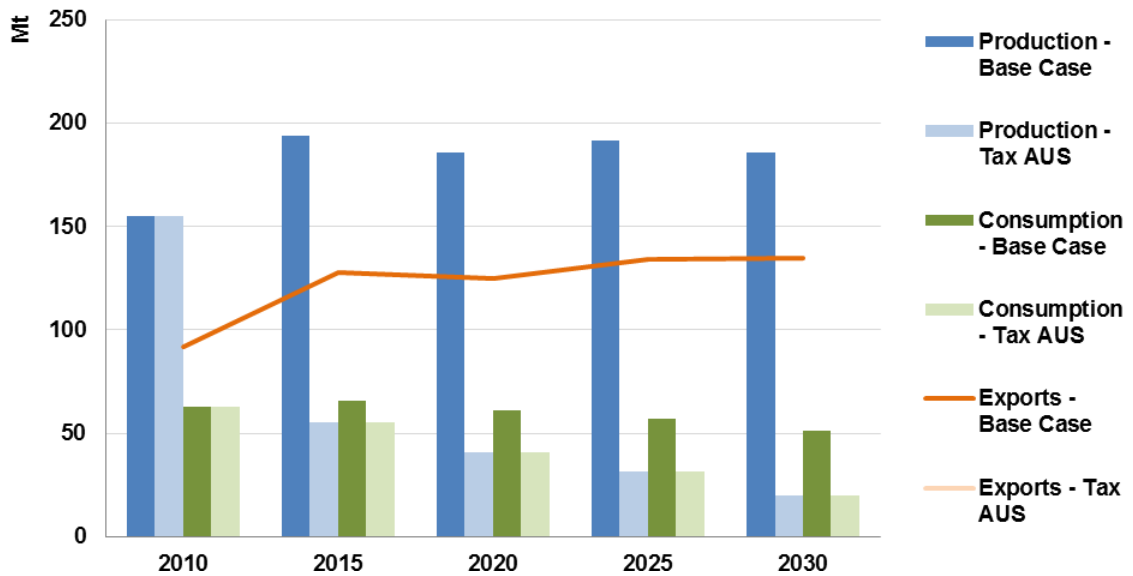


Figure 9: The impact of the optimal production tax on Australian production, exports and consumption relative to the *Base Case*, in Mt.

## 4.2 Scenario 2: A Jointly Set Export 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 option. 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<sub>2</sub>, or 22-26 USD per tonne of exported steam coal (depending on the energy content of the respective coal). This is significantly higher than the unilaterally introduced Australian export tax.

The NPV of joint tax revenues is about 125 bn. USD; the Australian share (without considering a coalition distribution scheme yet) is 16 bn. USD, which is about the level of revenue in the unilateral *Tax AUS* case. Figure 10 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, 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 11 shows that, for a given tax level, the "*Tax Coalition*" case always has higher average revenue per tonne of CO<sub>2</sub> avoided (a market power effect) and higher cumulative emission reductions than the "*Tax AUS*" case. Note that for the optimal tax rate the level of average additional revenue is at about 19 USD/tCO<sub>2</sub> (at cumulative CO<sub>2</sub> emission reduction of 900 Mt CO<sub>2</sub>) for the "*Tax AUS*" case while its is 30 USD/tCO<sub>2</sub> (at cumulative CO<sub>2</sub> emission reduction

of 4100 Mt CO<sub>2</sub>) for the "Tax Coalition" case.

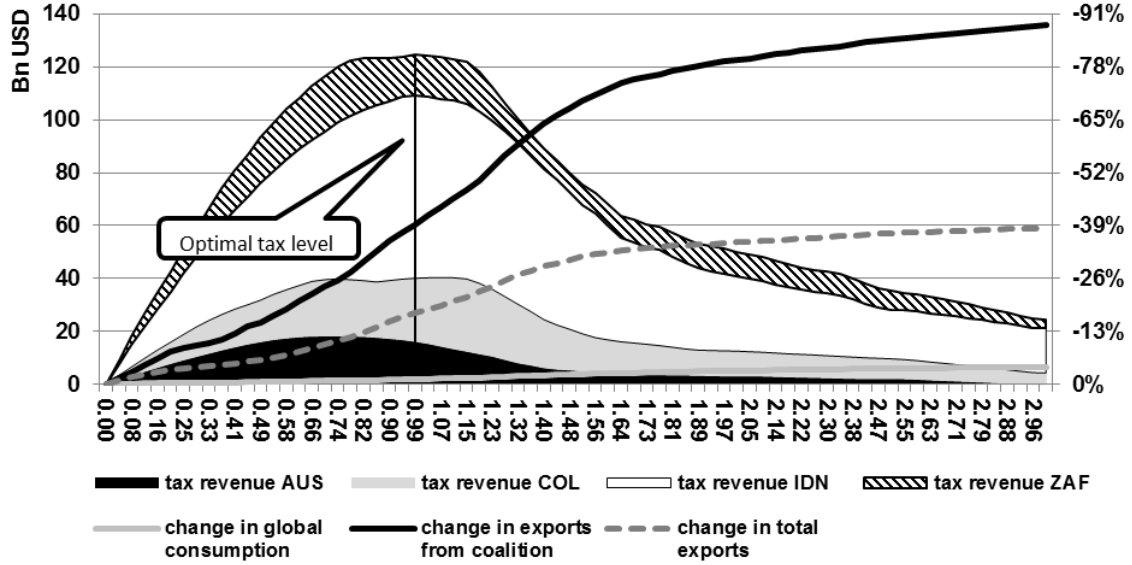


Figure 10: NPV of tax revenues of coalition members, in bn. USD; and change in global consumption, export for all coalition members and total exports, in %; as a function of the starting value of the export tax, in USD/GJ.

Taking again an Australian perspective, Figure 12 shows how tax revenue and welfare maximization are both improved in the situation of a cooperatively acting coalition. This is due to the a reduced set of countries countervailing the Australian rent seeking policy behaviour.

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 pronounced, and global consumption is reduced to a larger extent than in the unilateral Australian tax case. Global CO<sub>2</sub> emissions are reduced by on average to 200 Mt CO<sub>2e</sub>

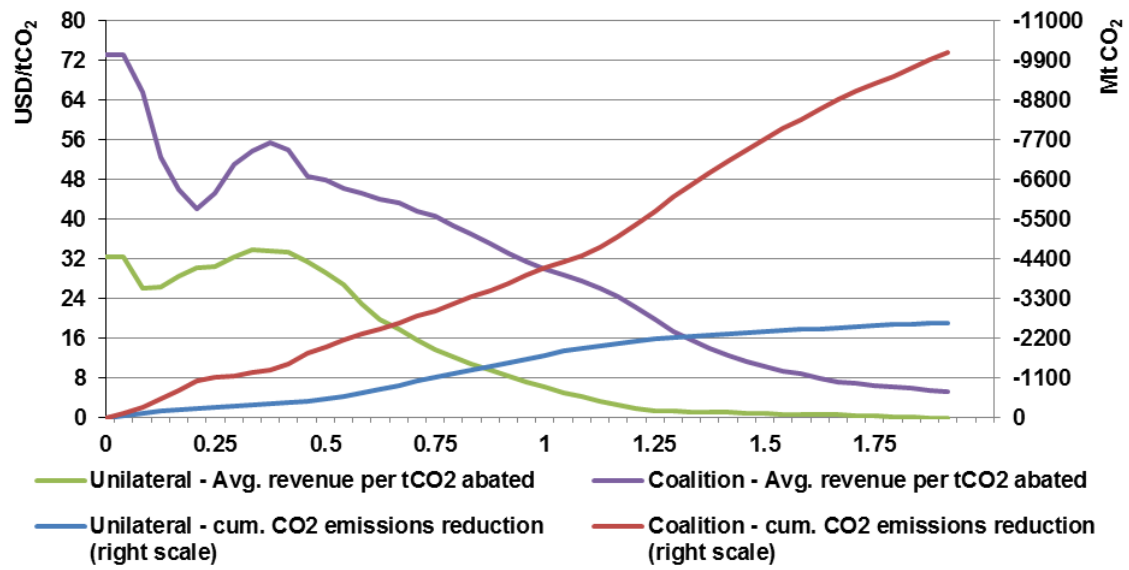


Figure 11: Comparison of average revenue per tonne of CO<sub>2</sub> abated and cumulative CO<sub>2</sub> emissions reduction in "Tax AUS" and "Tax Coalition", in USD/tCO<sub>2</sub> and Mt CO<sub>2</sub>.

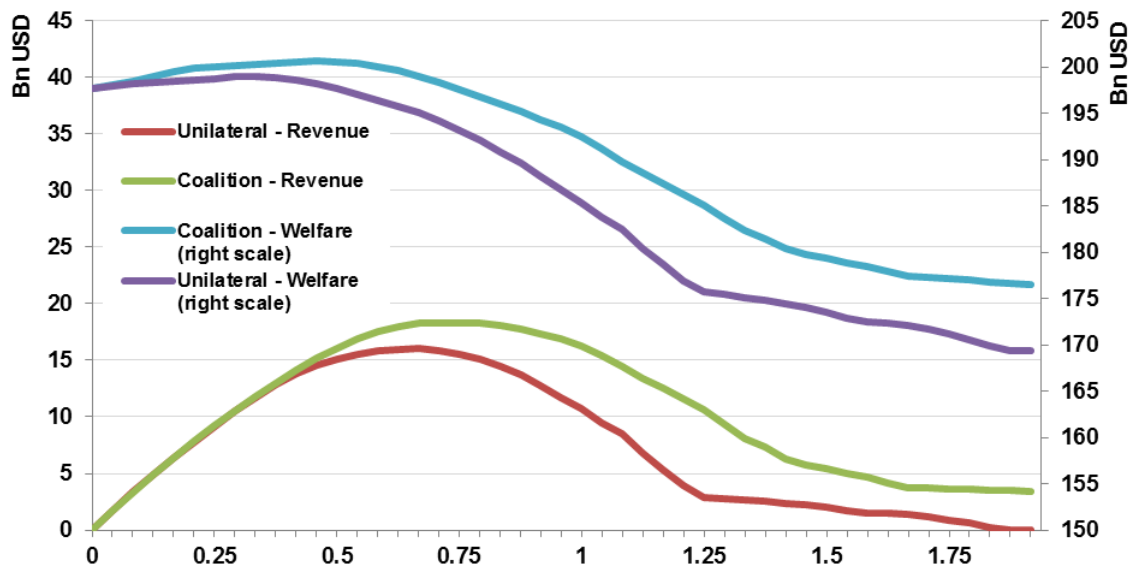


Figure 12: Comparison of Australian tax revenue and welfare (right axis) between the unilateral export tax and the jointly set export tax by major exporters, in bn. USD.

per year, compared to 37 Mt CO<sub>2e</sub> per year in the unilateral case. Figure 13 summarizes these volume effect of the coalition's export tax. It also shows the effect of the tax on average coal prices for the consumers. The relative price increase is most pronounced in the year when 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.

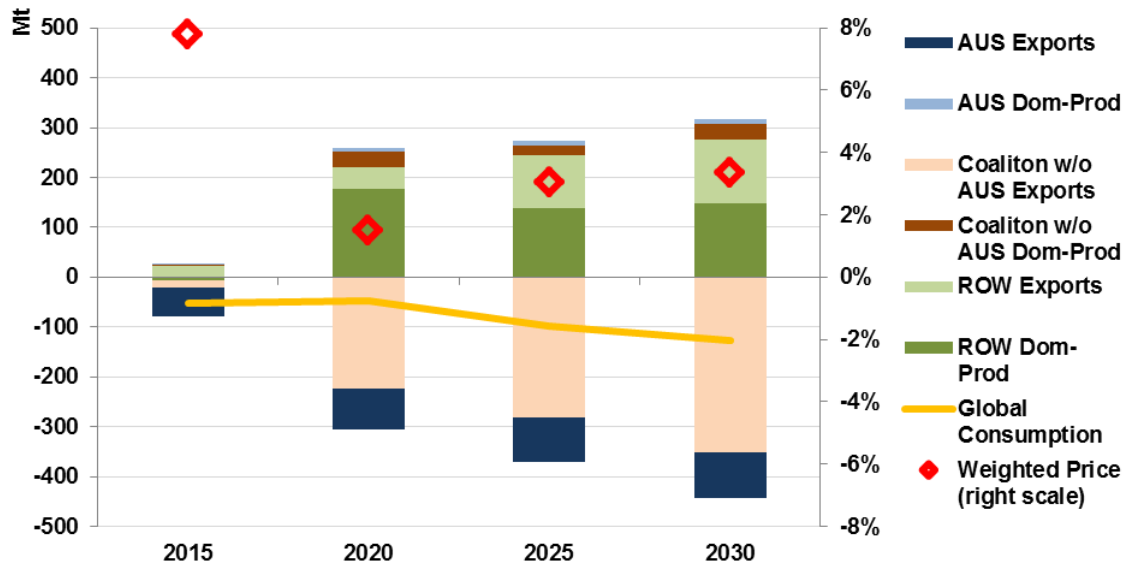


Figure 13: Decomposed impact of an export tax jointly set by the coalition of major exporters relative to the *Base Case*, in Mt, and change in weighted CIF prices in %.

#### 4.2.1 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; namely by 20% higher than the coalition's export tax at a level of 1.2 USD/GJ, or 12.2 USD/tCO<sub>2</sub>. Figure 14 depicts the decomposition of tax revenues across members and shows how global emission reduce with the initial production tax level. Notably, the tax revenue as a function of the initial tax level has again two peaks, like in the unilateral tax scenario, but here the first peak yields the higher revenue. In contrast to an export tax, the coalition's

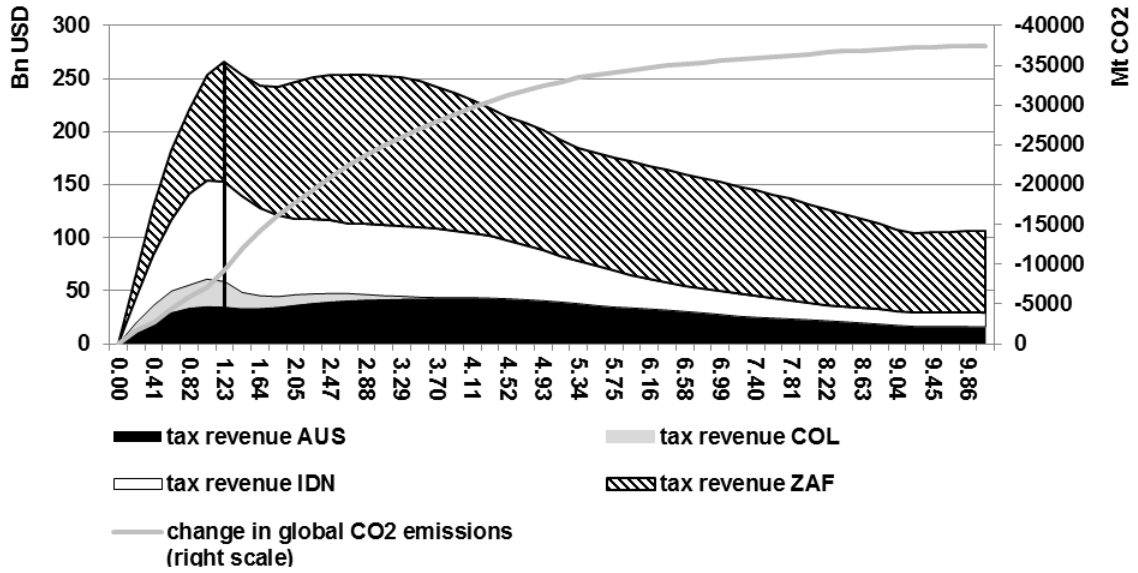


Figure 14: Tax revenue of the coalition's members and change in global CO<sub>2</sub> emission as a function of the initial common production tax rate, in USD/GJ.

supply to its domestic market is substantially reduced. Overall, both production and exports levels are reduced by almost 50% in 2030 relative to the *Base Case*. Cumulative CO<sub>2</sub> emissions can be reduced by 9 Gt. In this scenario South Africa, with its high and increasing domestic coal demand, has a dominate 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%.

#### 4.2.2 Coalition joint by the USA

As a sensitivity of our results to the members of the coalition we also examine a case with the USA joining the aforementioned coalition. In this case we find the optimal initial tax level at 1.2 USD/GJ, or 12.2 USD/tCO<sub>2</sub> <sup>21</sup>, and total coalition revenue rising to 150 bn. USD. While the effect of including the U.S. into the coalition is quite pronounced (2.1 USD/tCO<sub>2</sub> increase in optimal tax level, 30 bn. USD additional revenue), the U.S. share of the generated revenue is rather small compared to the other members (c.f. Figure 15). This poses the question of how the revenue is to be distributed, which we leave to further research. The high tax put price under pressure and leads to a price increase of on average 8.5% (see Figure 16). Competing exporters and domestic producers are increasingly unable to compensate for the restrained exports which lead to a 3% decrease in global consumption over the modelling period.

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<sup>21</sup>The exact match with the level of the production-based tax in section 4.2.1 is due to impression in the calculation method and does not bring any implications

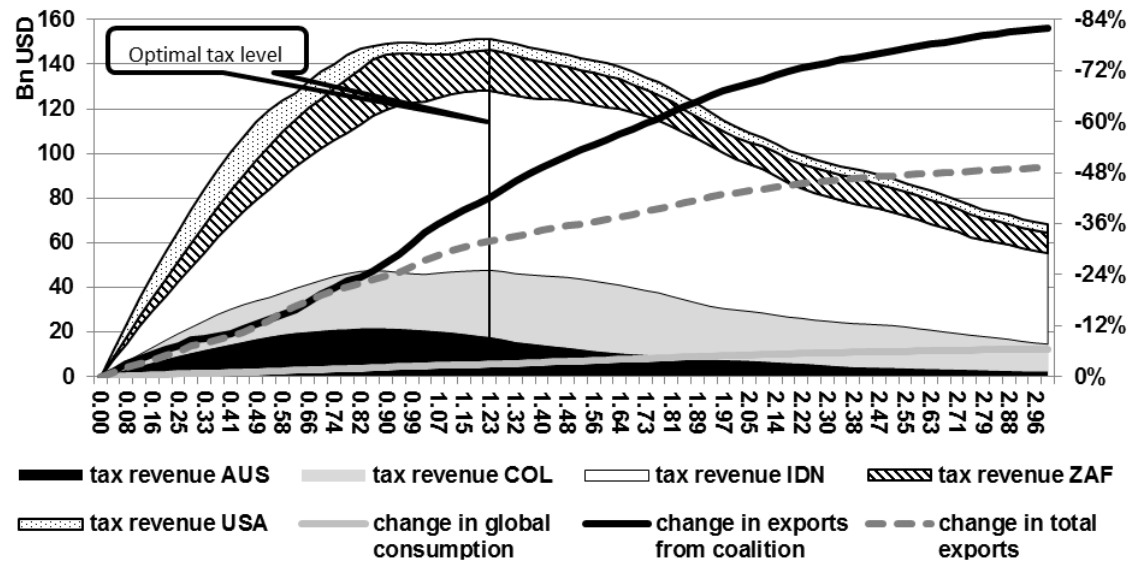


Figure 15: NPV of tax revenues of coalition members, in bn. USD; and change in global consumption, export for all coalition members and total exports, in %; as a function of the starting value of the export tax, in USD/GJ.

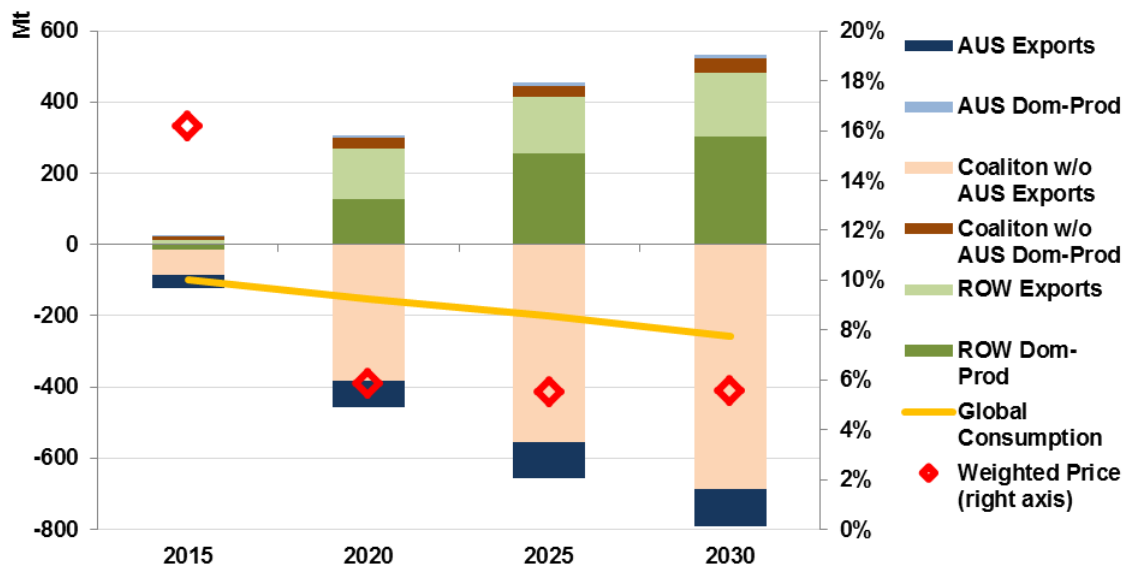


Figure 16: Decomposed impact of an export tax jointly set by the coalition (including USA) of major exporters relative to the *Base Case*, in Mt, and change in weighted CIF prices in %.

### 4.3 Qualification of Results

The conducted analysis 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 will partly ramp up the consumption of natural gas and crude oil; effects on CO<sub>2</sub> emissions reductions from lower coal consumption are hence 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 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 Conclusion

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 two-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<sub>2</sub> 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.

## Appendix

### A.1 List of Endogenous Variables

Table A.1: Endogenous Variables

Variable	Description
$\tau_0^e$	Starting value of export 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
$\alpha_{af}^P$	Dual variable to production capacity constraint
$\alpha_{af}^{inv^P}$	Dual variable to max. investment in production capacity constraint
$\alpha_f^{res}$	Dual variable to reserve constraint
$\alpha_{afc}^{TC}$	Dual variable to transport capacity to consumer constraint
$\alpha_{afe}^{TE}$	Dual variable to transport capacity to exporter constraint
$\mu_{ae}^E$	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

Producer's KKTs:

w.r.t  $x_{afc}$ :

$$\begin{aligned}
& \left( \frac{1}{1+r_f} \right)^{a-1} \left[ -p_{ac} \right. \\
& + \kappa_f \cdot mc_{af}^{int} + (\kappa_f)^2 \cdot mc_f^{slp} \left( \sum_c x_{afc} + \sum_e y_{afe} \right) \\
& + \kappa_f \cdot trans_{fc}^{TC} + \kappa_f \cdot \alpha_{af}^P + \sum_{a'>a} \kappa_f \cdot \alpha_{f,a'}^P \cdot mc_f^{int-var} \left. \right] \\
& + 5 \cdot \kappa_f \cdot \alpha_f^{res} + \kappa_f \cdot \alpha_{afc}^{TC} \geq 0
\end{aligned} \tag{A.1}$$

w.r.t  $y_{afe}$ :

$$\begin{aligned}
& \left( \frac{1}{1+r_f} \right)^{a-1} \left[ -p_{a,e} \right. \\
& + \kappa_f \cdot mc_{af}^{int} + (\kappa_f)^2 \cdot mc_f^{slp} \left( \sum_{c'} x_{afc'} + \sum_{e'} y_{afe'} \right) \\
& + \kappa_f \cdot trans_{fe}^E + \kappa_f \cdot \alpha_{af}^P + \sum_{a'>a} \kappa_f \cdot \alpha_{f,a'}^P \cdot mc_f^{int-var} \left. \right] \\
& + 5 \cdot \kappa_f \cdot \alpha_f^{res} + \kappa_f \cdot \alpha_{afe}^{TE} \geq 0
\end{aligned} \tag{A.2}$$

w.r.t  $inv_{af}^P$ :

$$\left( \frac{1}{1+r_f} \right)^{a-1} Cinv_f^P - \sum_{a'>a} \alpha_{a'f}^P + \alpha_{af}^{inv^P} \geq 0; \tag{A.3}$$

w.r.t.  $inv_{afc}^{TC}$

$$\left( \frac{1}{1+r_f} \right)^{a-1} Cinv_{fc}^{TC} - \sum_{a'>a} \alpha_{a'fc}^{TC} \geq 0; \tag{A.4}$$



w.r.t.  $inv_{afe}^{TE}$

$$\left(\frac{1}{1+r_f}\right)^{a-1} Cinv_{fe}^{TE} - \sum_{a'>a} \alpha_{a'fe}^{TE} \geq 0; \quad (A.5)$$

w.r.t  $\alpha_{af}^P$

$$\begin{aligned} cap_f^p + \sum_{a'<a} \left[ inv_{a'f}^P - \left( \sum_c \kappa_f \cdot x_{a'fc} + \sum_e \kappa_f \cdot y_{a'fe} \right) \cdot mc_f^{int-var} \right] \\ - \left( \sum_c \kappa_f \cdot x_{afc} + \sum_e \kappa_f \cdot y_{afe} \right) \geq 0; \end{aligned} \quad (A.6)$$

w.r.t.  $\alpha_{af}^{inv^P}$ :

$$\overline{inv}_f^P - inv_{af}^P \geq 0; \quad (A.7)$$

w.r.t.  $\alpha_{afc}^{TC}$ :

$$cap_{fc}^{TC} + \sum_{a'<a} inv_{a'fc}^{TC} - \kappa_f x_{afc} \geq 0; \quad (A.8)$$

w.r.t.  $\alpha_{afe}^{TE}$ :

$$cap_{fe}^{TE} + \sum_{a'<a} inv_{a'fe}^{TE} - \kappa_f y_{afe} \geq 0; \quad (A.9)$$

w.r.t.  $\alpha_f^{res}$ :

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

Endogenous intercept  $mc_{af}^{int}$ :

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

### Exporter's KKTs

w.r.t  $z_{aec}$ :

$$\begin{aligned} & \left( \frac{1}{1+r_e} \right)^{a-1} \left[ -p_{ac} + p_{ae} + fee_e \cdot \kappa_e + sea_{aec} \cdot \kappa_e + \tau_a^e \right] \\ & + \kappa_e \cdot \mu_{ae}^E \geq 0 \quad \perp \quad z_{aec}, \end{aligned} \quad (\text{A.12})$$

w.r.t  $inv_{ae}^E$ :

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

w.r.t  $\mu_{ae}^E$ :

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

w.r.t  $\mu_{ae}^{inv^E}$ :

$$\overline{inv}_e^E - inv_{ae}^E \geq 0; \quad (\text{A.15})$$

### Market clearing exporter & demand:

$$\sum_f y_{afe} = \sum_c z_{aec}; \quad (\text{A.16})$$

$$p_{ac}^c = Dint_{ac} + b_{ac} \cdot \left( \sum_f x_{afc} + \sum_e z_{aec} \right) \quad (\text{A.17})$$

### Political Restriction China:

$$China_{ae}^{lic} - \sum_{c' \neq Chn} \kappa_e \cdot z_{aec'} \geq 0; \quad \text{for } e = 'CHN' \quad (\text{A.18})$$

### A.3 Solution Algorithm

Figure A.1 depicts how these methods are tied together by our solution approach.

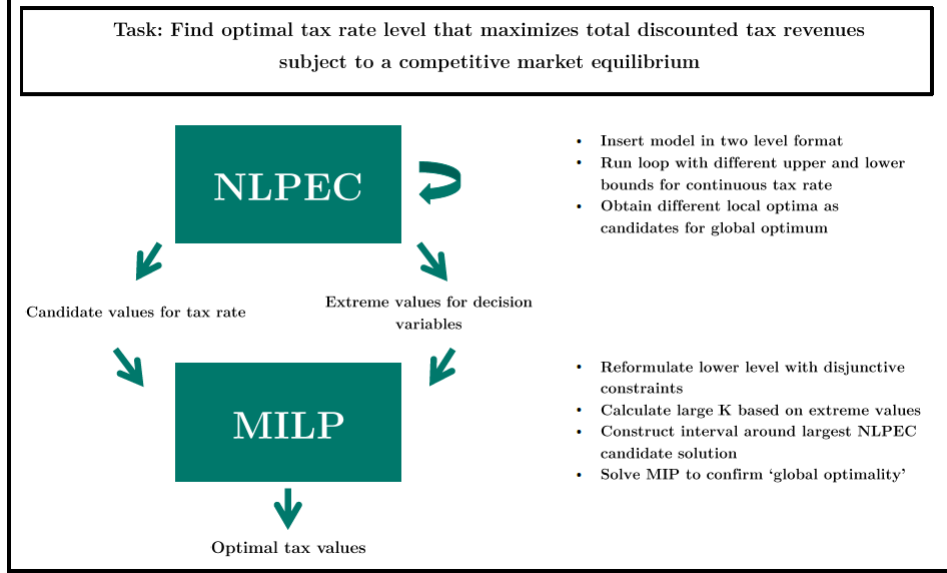


Figure A.1: Illustration of Solution Strategy

#### A.3.1 GAMS NLPEC solver

In a first step, 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  $\tau_0^e$ . Furthermore, extreme values for all variables are reported. 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.

Taking as example the optimization problem of exporter  $e$ , we derive the KKT condition with respect to exported quantities  $z_{aec}$  as

$$d\Pi_e/dz_{aec} = \left( \frac{1}{1+r_e} \right)^{a-1} \left[ -p_{ac} + p_{ae} + fee_e \cdot \kappa_e + sea_{aec} \cdot \kappa_e + \tau_a^e \right] + \kappa_e \cdot \mu_{ae}^E \geq 0 \quad \perp \quad z_{aec}, \quad (\text{A.19})$$

while the KKT condition with respect to investments in capacity expansions  $inv_{ae}^E$  is given by

$$d\Pi_e/dinv_{ae}^E = \left(\frac{1}{1+r_e}\right)^{a-1} \left(Cinv_e^E + \sum_{a'>a} \mu_{a'e}^E + \mu_{ae}^{inv^E}\right) \geq 0 \quad \perp \quad inv_{ae}^E. \quad (\text{A.20})$$

### A.3.2 MIP formulation

In a second step, we test the candidate NLPEC solution, which has the highest upper-level objective value, for optimality by formulating a MILP. For this purpose both the upper, and lower level needs to be linearised. The lower-level complementarity conditions (i.e. the duality between equation and respective variable) are 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.19) by means of disjunctive constraints as follows

$$0 \leq \left(\frac{1}{1+r_e}\right)^{a-1} \left[ -p_{ac} + p_{ae} + fee_e \cdot \kappa_e + sea_{aec} \cdot \kappa_e + \tau_a^e \right] + \kappa_e \cdot \mu_{ae}^E \leq bin_{aec}^z \cdot K_{aec}^z \quad (\text{A.21})$$

$$0 \leq z_{aec} \leq (1 - bin_{aec}^z) \cdot K_{aec}^z. \quad (\text{A.22})$$

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  $\tau_{0,d}^e$ , where index  $d$  denotes predetermined discrete options for the export tax. Each potential tax rate is related to a binary variable  $bin_d^\tau$  and a sufficiently large positive constant  $K_d^\tau$ . In essence, the algorithm 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

$$obj = \max \sum_d rev_d \quad (A.23)$$

$$rev(d) \leq \sum_{aec'} \left( \frac{1}{1 + r_g} \right)^{a-1} [\tau_{0d}^e \cdot (1 + r_\tau)^{a-1} EXP_{aec'}] \quad (A.24)$$

$$\sum_d bin_d^\tau = 1 \quad (A.25)$$

$$rev(d) \leq K_d^\tau \cdot bin_d^\tau \quad (A.26)$$

While Eq. (A.23) maximises the sum of potential tax revenues  $rev_d$  over all possible discrete choices, Eq. (A.24) links these revenues to the different tax rate options. By Eq. (A.25) it is guaranteed that only one tax options is chosen, while Eq. (A.26) only allows for the respective tax revenue to be positive. This ensures that Eq. (A.23) 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 constraint set of choices.<sup>22</sup>

#### A.4 Model Specification

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<sup>22</sup>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).

Table A.2: Nodes of COALMOD-World.

Source: *Holz et al. (2015)*

Country	Producers	Exporters	Consumers	Port
Canada	<i>P_CAN</i>		<i>C_CAN</i>	Ontario
USA	<i>P_USA_PRB</i>	<i>E_USA_SC</i>	<i>C_USA_W</i>	AK, AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA, WY
	<i>P_USA_Rocky</i>	<i>E_USA_SE</i>	<i>C_USA_NC</i>	IL, IN, IA, KS, MI, MN, NE, MO, ND, OH, SD, WI
	<i>P_USA_ILLL</i>	<i>E_USA_W</i>	<i>C_USA_SC</i>	AR, LA, OK, TX
	<i>P_USA_APP</i>		<i>C_USA_SE</i>	AL, DE, DC, FL, GA, KY, MD, MS, NC, SC, TN, VA, WV
Colombia	<i>P_COL</i>	<i>E_COL</i>	<i>C_USA_NE</i>	CT, ME, MA, NH, NJ, NY, PA, RI, VT
Venezuela	<i>P_VEN</i>	<i>E_VEN</i>		
Morocco			<i>C_MAR</i>	Mohammedia
Portugal			<i>C_PRT</i>	Sines
Spain			<i>C_ESP</i>	Gijon
UK			<i>C_GBR</i>	Inningham
Netherlands/ France/Belgium			<i>C_NFB</i>	Rotterdam
			<i>C_DEU</i>	Rotterdam + land transport
Germany			<i>C_DNK</i>	Aalborg
Denmark			<i>C_FIN</i>	Kotka
Finland			<i>C_ITA</i>	Taranto
Italy			<i>C_POL</i>	No
Poland	<i>P_POL</i>	<i>E_POL</i>	<i>C_TUR</i>	Mersin + Black sea port
Turkey			<i>C_ISR</i>	Ashdod
Israel	<i>P_UKR</i>	<i>E_Black_Sea_UKR</i>	<i>C_UKR</i>	No
Ukraine	<i>P_KAZ</i>	<i>E_RUS_West</i>	<i>C_KAZ</i>	No
Kazakhstan	<i>P_RUS</i>	<i>E_RUS_East</i>	<i>C_RUS_Central</i>	No
Russia		<i>E_Black_Sea_RUS</i>	<i>C_RUS_Siberia</i>	No
South Africa	<i>P_ZAF</i>	<i>E_ZAF</i>	<i>C_ZAF</i>	No
India	<i>P_IND_North</i>		<i>C_IND_East</i>	Bihar, Chhattisgarh, Jharkhand, Orissa, West Bengal
	<i>P_IND_Orissa</i>		<i>C_IND_North</i>	Delhi, Punjab, Rajasthan, Uttar Pradesh
	<i>P_IND_West</i>		<i>C_IND_West</i>	Gujarat, Madhya Pradesh, Maharashtra
	<i>P_IND_South</i>		<i>C_IND_South</i>	Andhra Pradesh, Karnataka, Tamil Nadu
Thailand			<i>C_THA</i>	Chennai
Malaysia			<i>C_MYS</i>	Bangkok
Vietnam	<i>P_VNM</i>			Port Klang
Indonesia	<i>P_IDN</i>	<i>E_IDN</i>	<i>C_IDN</i>	No
China	<i>P_CHN_SIS</i>	<i>E_CHN</i>	<i>C_CHN_Northeast</i>	Heilongjiang, Jilin, Liaoning
	<i>P_CHN_Northeast</i>		<i>C_CHN_Main</i>	Beijing, Tianjin, Hebei, Henan, Shandong, Tianjin
	<i>P_CHN_HSA</i>		<i>C_CHN_Eastern</i>	Anhui, Jiangsu, Hubei, Shanghai, Zhejiang
	<i>P_CHN_YG</i>		<i>C_CHN_South</i>	Chongqing, Fujian, Guangdong, Guangxi, Guizhou, Hong Kong, Huanan, Jiangxi, Sichuan
Korea			<i>C_CHN_SIS</i>	Shanxi, Shaaxi, Inner Mongolia
Japan			<i>C_KOR</i>	No
Taiwan			<i>C_JPN</i>	Ulsan
Philippines			<i>C_TWN</i>	Yokohama
Australia	<i>P_AUS_QLD</i>	<i>E_AUS_QLD</i>	<i>C_PHL</i>	Kaohsiung
	<i>P_AUS_NSW</i>	<i>E_AUS_NSW</i>	<i>C_AUS</i>	Manila
Mozambique	<i>P_MOZ</i>	<i>E_MOZ</i>		No
Mongolia	<i>P_MNG</i>			

## A.5 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	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

\*net with 20 Mt exports to Taiwan in 2010

A.6 Global Trade Flows in 2030 by Case

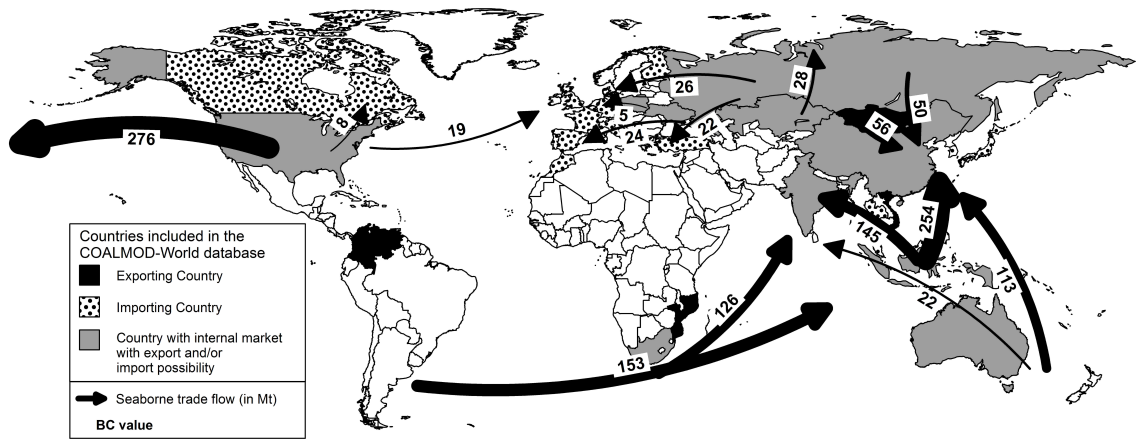


Figure A.2: Global Trade Flows in the *Base Case* in 2030, in Mt.

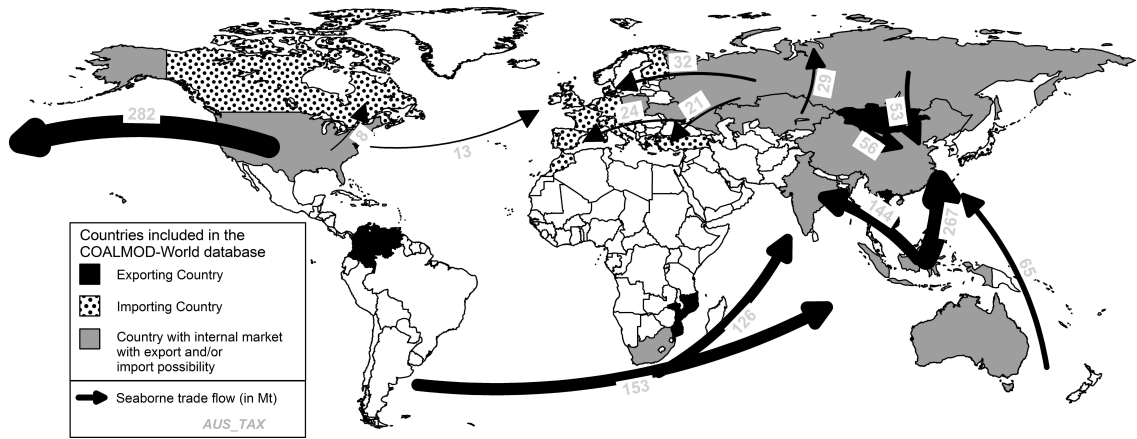


Figure A.3: Global Trade Flows in *Tax AUS* in 2030, in Mt.





Figure A.4: Global Trade Flows in *Tax Coalition* in 2030, in Mt.

## A.7 Production Tax - Adjusted Equations

The tax path in Eq. (1) now holds for production tax  $\tau_a^p$ :

$$\tau_a^p = \tau_0^p \cdot (1 + r_\tau)^{a-a'} \quad (\text{A.27})$$

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

$$obj_g = \max_{\tau_0^p} \sum_{af} \left( \frac{1}{1 + r_g} \right)^{a-1} \cdot \tau_a^p \cdot PROD_{af}, \quad (\text{A.28})$$

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.

$$\begin{aligned}
\max_{x_{afc}, y_{afe}, inv_{af}^P, inv_{afc}^{TC}, inv_{afe}^{TE}} \Pi_f = & \sum_a \left( \frac{1}{1+r_f} \right)^{a-1} \cdot \left[ \right. \\
& \sum_c p_{ac} \cdot x_{afc} + \sum_e p_{ae} \cdot y_{afe} - C_{prod_{af}}[x_{afc}, y_{afe}] \\
& - \left( \sum_c x_{afc} + \sum_e y_{afe} \right) \cdot \tau_a^p \\
& - \sum_c trans_{afc}^C \cdot \kappa_f \cdot x_{afc} - \sum_e trans_{afe}^E \cdot \kappa_f \cdot y_{afe} \\
& \left. - C_{inv_{af}}^P \cdot inv_{af}^P - \sum_c C_{inv_{afc}}^{TC} \cdot inv_{afc}^{TC} - \sum_e C_{inv_{afe}}^{TE} \cdot inv_{afe}^{TE} \right], \tag{A.29}
\end{aligned}$$

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

$$\begin{aligned}
\max_{z_{aec}, inv_{ae}^E} \Pi_e = & \sum_a \left( \frac{1}{1+r_e} \right)^{a-1} \cdot \left[ \sum_c p_{ac} \cdot z_{aec} \right. \\
& - \sum_c (p_{ae} \cdot z_{aec} + fee_e \cdot \kappa_e \cdot z_{aec} + sea_{aec} \cdot \kappa_e \cdot z_{aec}) \\
& \left. - C_{inv_{ae}}^E \cdot inv_{ae}^E \right]. \tag{A.30}
\end{aligned}$$

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