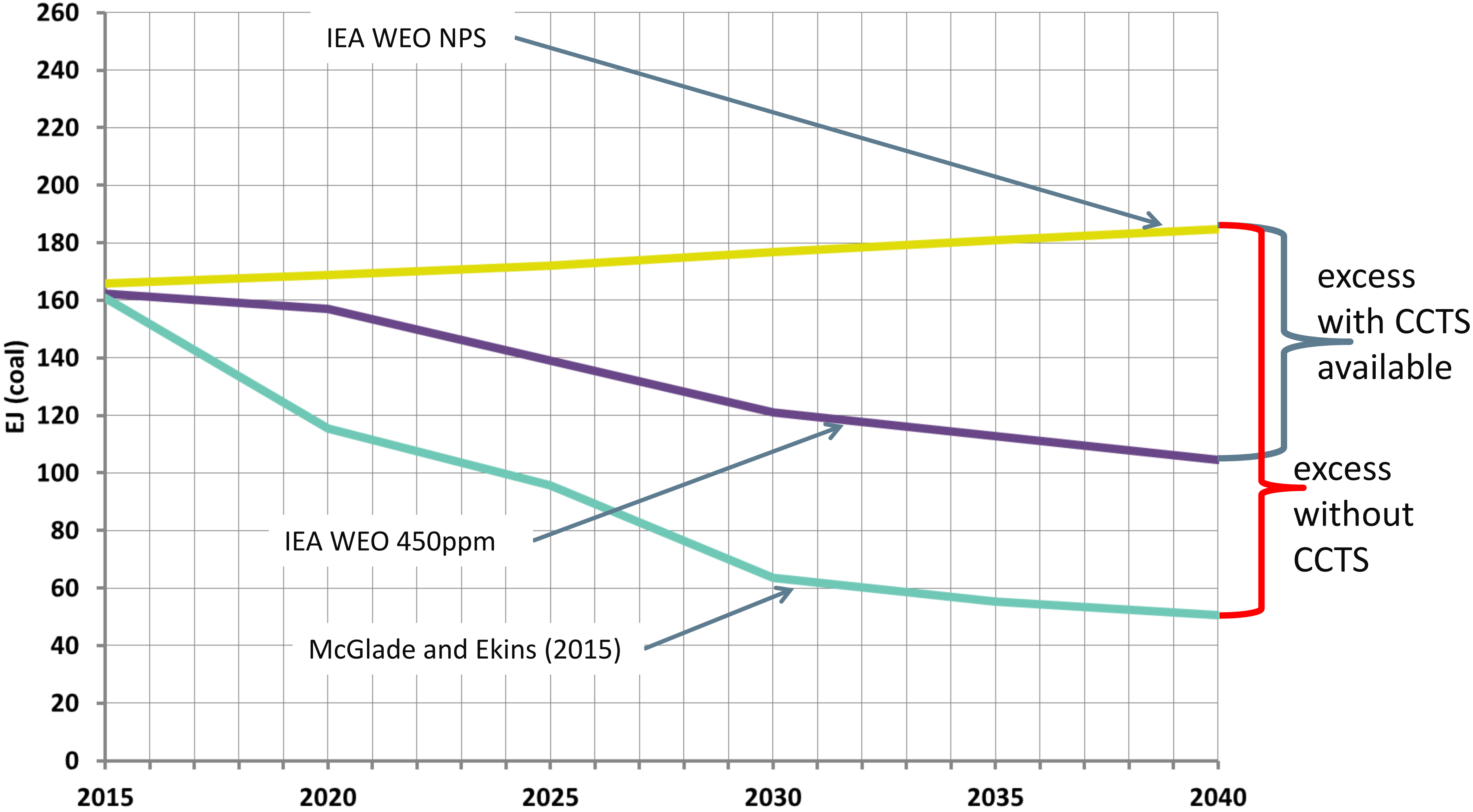
Testing Supply-Side Climate Policies for the Global Steam Coal Market

Can they curb coal consumption?

Mendelevitch, Roman , Humboldt Universität zu Berlin

BELEC 2016, Berlin, October, 13th 2016

Motivation
Projections of coal consumption from various sources



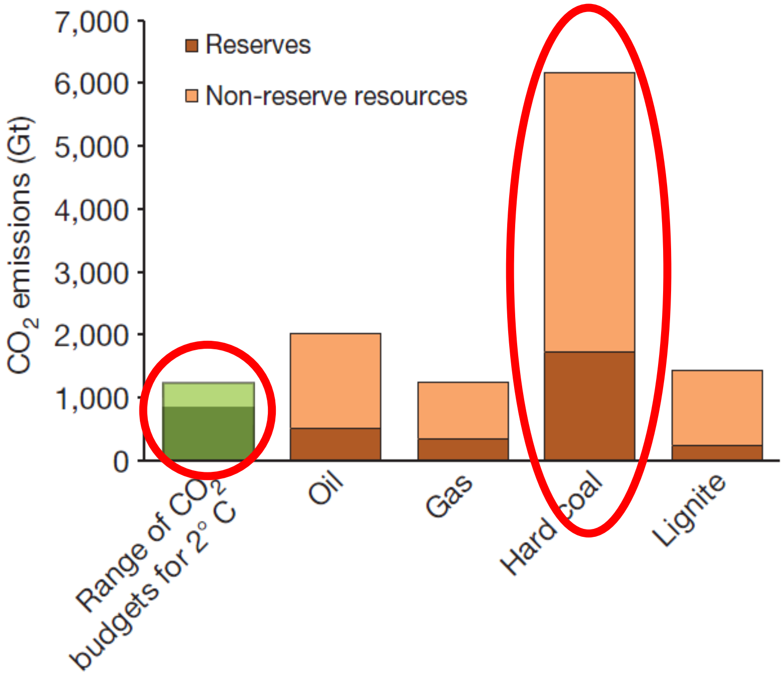
Content

2 Demand-side vs. supply-side fossil fuel policies

- What currently favors demand-side policies
  - Less opposition with promoting new industries e.g. renewables energies, that with closing old ones
  - GHG accounting at the national level
  - Capturing of climate rents at the demand-side

- Why supply-side policies are good complements
  - Address green paradox
  - Prevent stranded assets and lock-in effects
  - Allow for additional rents on the supply-side
  - Scarcity rents can offset lost profits (Eisenack, Edenhofer, and Kalkuhl 2012; Kalkuhl and Brecha 2013; Asheim 2013)
  - No need for overall compensation, only compensation payments between producers to alleviate internal distributional effects (Asheim 2013)

Source: McGlade and Ekins (2015)



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Policy options to achieve CO_2 emission reductions (adapted from Lazarus, Erickson, and Tempest, 2015)

	Demand-side policy	Supply-side policy
Economic Instruments	Carbon or fuel use taxes Border carbon price adjustments	Resource export/production tax
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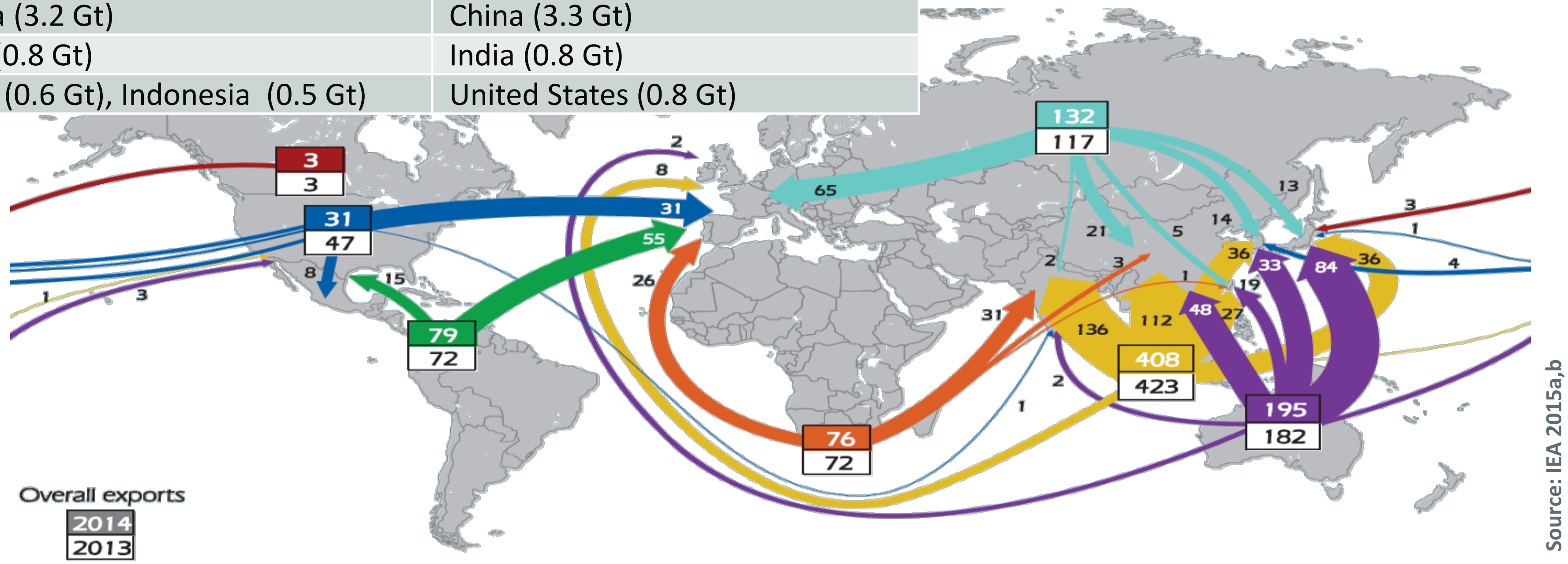
	Building codes	Assessment in environmental impact review of new fossil fuel supply projects
Public provision of goods and services	Infrastructure expansion Policies to restrict export credit agency finance for fossil fuel projects	Restricted leasing of state-owned lands/waters Decision to not develop specific resources or infrastructure Funding to compensate resource owners for leaving reserves undeveloped
Information, and other	Energy audits Vehicle or appliance labelling Territorial emissions accounting	Divestment by institutions/companies involved in fossil fuel production Extraction-based emissions accounting life-cycle based accounting of embedded GHGs in fossil fuels sold in marketplace

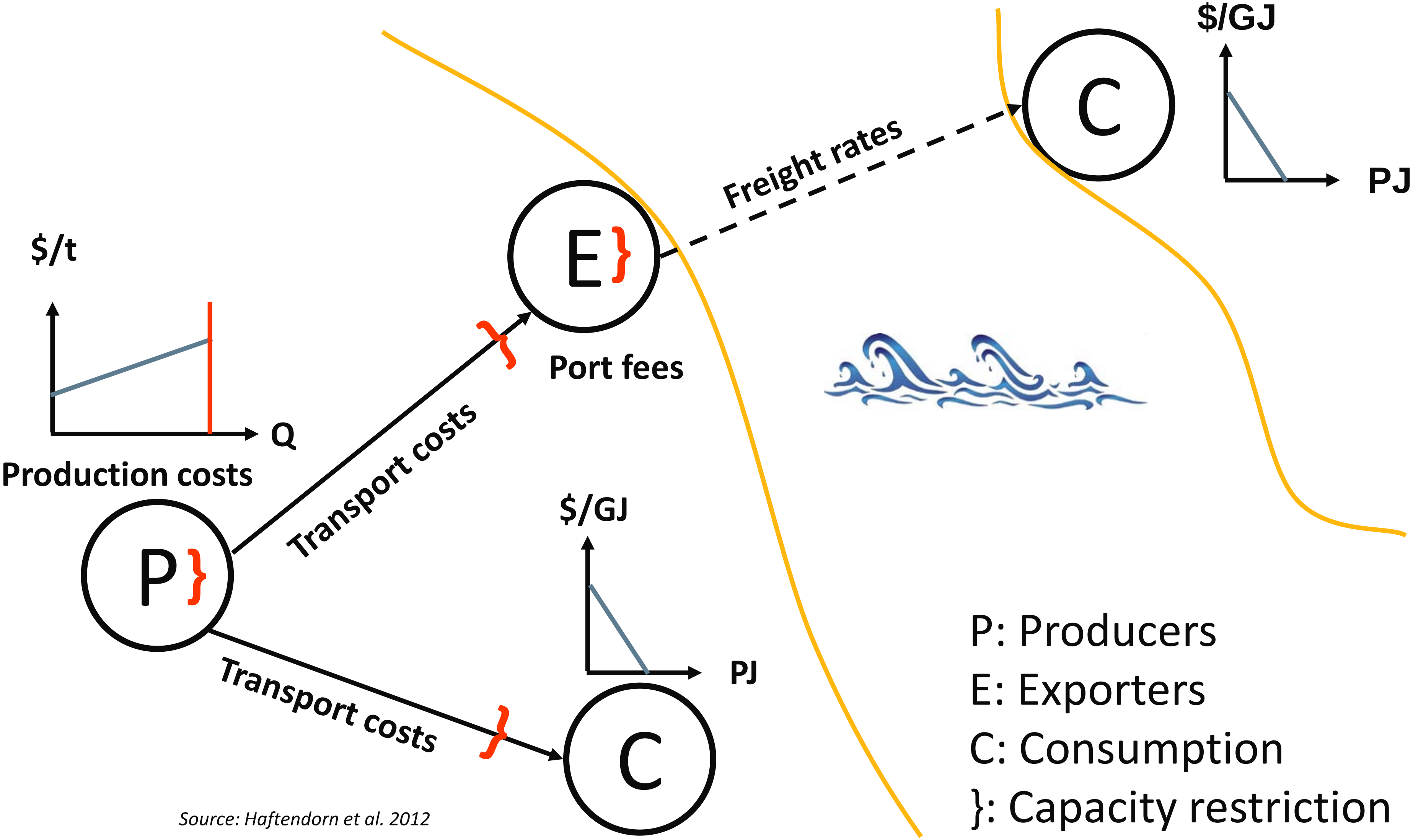
Content

3 Quantitative assessment using COALMOD-World

Major producers in 2014 (6.1 Gt)	Major consumers in 2014
China (3.2 Gt)	China (3.3 Gt)
USA (0.8 Gt)	India (0.8 Gt)
India (0.6 Gt), Indonesia (0.5 Gt)	United States (0.8 Gt)



3 Structure of COALMOD-World



P: Producers
E: Exporters
C: Consumption
}: Capacity restriction

Source: Haftendorn et al. 2012

3 Setting-up a two-level game as an Mathematical Program with Equilibrium Constraints (MPEC)

Optimization

Upper level

- country g maximize the NPV of tax revenues
- market reactions are taken into account (lower level)
- Decision variable: (starting value) of an (energy based) export tax

Equilibrium problem

Lower level

- Large-scale multi-period equilibrium model of a competitive steam coal market (modeled as MCP) initially developed by Haftendorn et al. 2012 and Holz et al. 2015
- Profit-maximizing players with specific constraints
- Market clearing via inverse demand functions
- Endogenous investment in production and export capacities
- Substitution between importing and domestic production

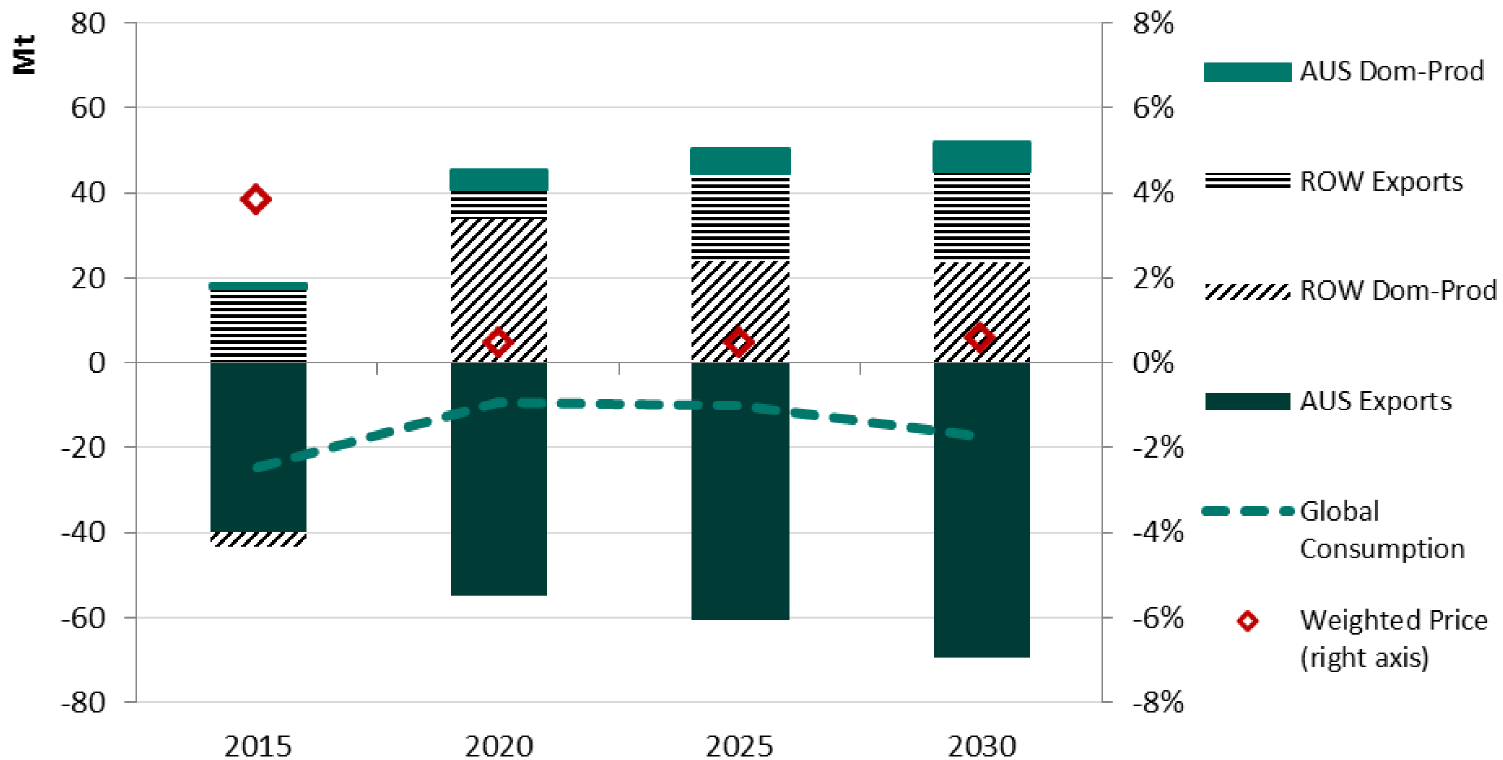
Content

4 Case – Australian Export Tax

Four partial effects on the mass balances relative to the *Base Case:*

1. Australian exports are reduced
2. Australian domestic consumption is increased
3. RoW production is increased
    - Exporting competitors increase their supply
    - Importing countries increase domestic production
4. RoW consumption is reduced

4 Case – Australian Export Tax - Global Impact



- Unilaterally reduced Australian production is largely compensated for (leakage of 70%)
- USA, Russia and Indonesia substitute Australian exports
- Domestic production increases esp. in China and India
- Volumes of seaborne trade are reduced by 40-50 Mt per year
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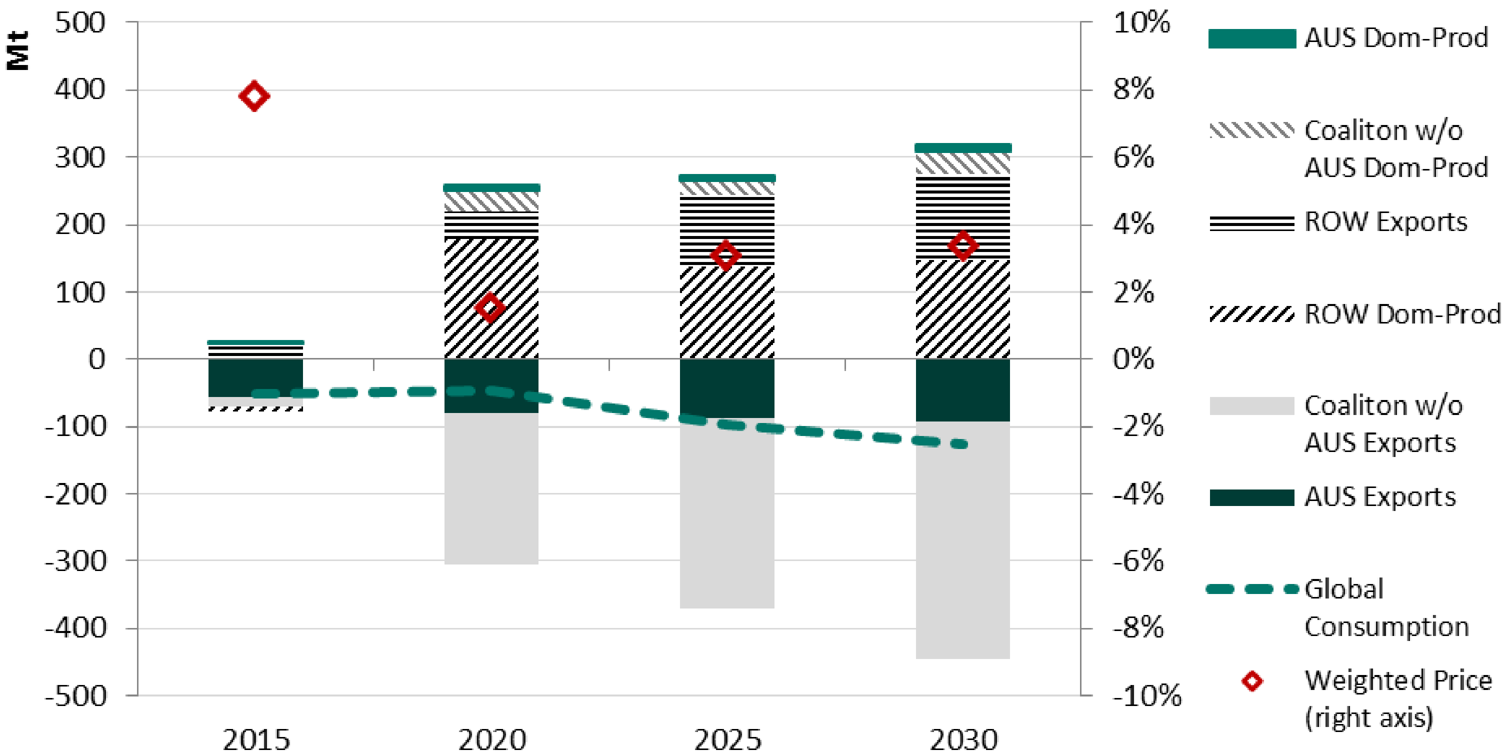
4 Case – Export Tax Set by Coalition Global Impact



- Smaller leakage effect, larger reduction in global consumption
- Emissions reduced by on average 200 Mt CO_2 per year
- Significant price increase due to export tax

4

Supply-side policy: coal tax
Grand tax coalition is required to be consistent with 2° target

	Supply-side tax scenarios			
	exporters grand coal.		prod. grand coal.	WEO 450ppm (implemented as demand-side policy)
	export tax	prod. tax		
Avg. emis. red. [$GtCO_2$/a]*	1.2	2.6	6.6	3.4
Red. in exports [%]*	74.9	55.1	50.1	30.8
Red. in global consump. [%]*	8.7	28.5	52.3	27.3
Avg. price change [%]*	15.8	34.4	111.6	-17.0
Optimal tax level [USD/tCO_2]	42.6	26.0	40.5	-

***where applicable value are given for the optimal tax level**

- Consumption pattern consistent with a 2° target cannot be achieve via an export tax, only, nor by a production tax levied by a coalition of coal exporting countries
- Only a global regime of taxing CO_2 from steam coal undercuts the required level
- Supply-side policies lead to strong price increase, while with demand-side policies prices decrease by on average 17%

Short Discussion of Approach

What we do take into account:

- Production increases of exporting competitors
- Substitution between domestic production and imports
- Endogenous capacity expansions

What we do not / cannot take into account:

- Fuel substitution in partial coal model
  - Only indirectly in demand function
  - Hence, upper level of emissions reductions
- Retaliation of other exporters or importers
- Endogenous paths of tax rate
- Stability of coalition or distribution mechanism
- General equilibrium effects of tax recycling and welfare effects

Content

1. Motivation
2. Demand-side vs. supply-side climate policies
3. The world steam coal market and COALMOD-World Model
4. Export/producer taxes
5. Subsidy removal
6. Mine Moratorium
7. Conclusions

Complex definition of Subsidies

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Consumer fossil-fuel subsidies	Producer fossil-fuel subsidies
Fossil fuels exempt from social cost of externalities (non-internalized externalities).	
Fossil fuels taxed below regional or international tax levels.	Government tax and regulation levels below regional or international levels.
Fossil fuels exempt from VAT, GST, and carbon taxes.	Government revenue foregone (reduced an exempt tax rates).
Fossil fuel sold below cost of production, imports and international benchmark price to consumers.	Direct transfers or potential direct transfers of funds to producers
	Income or price support (above market rate prices for producers).

Source: IEA, WB, OECD, IMF and GSI, 2014 and Gerasimchuk et al. 2012, adapted from Merrill 2014, and Bridle, 2014

“The term “subsidy” can be visualized as a nesting doll -
at the center of the definition are ideas that everyone agrees on,
but as the definition expands to include other layers, it becomes more complicated and more controversial.

5 Findings from literature on coal subsidies

- G20 (2009), APEC (2010), Friends of Fossil Fuel Subsidy Reform (GSI 2011), UN Secretary General's High-Level Panel on Global Sustainability (2012), UN Sustainable Development Goals (2015)
- range and magnitude of fossil fuel subsidies
  - OECD 2015: total 160-200 bnUSD annually , coal subsidies 12 bnUSD.
  - Ecofys 2014: 10 bnEUR coal subsidies in the EU-28, in 2012
  - IMF (Coady et al., 2015) 2,530 bn USD coal subsidies (globally)
- Effects on production subsidy removal in literature
  - Anderson and McKibbin (2000) CGE framework C-Cubed: 5%-8% global average emission reduction
  - Fulton et al. (2015) supply-demand partial equilibrium framework: removing subsidies for U.S Powder River Basin reduces annual emissions by 21-55 $MtCO_2$ per year

5 Coal Production Subsidies in the U.S.

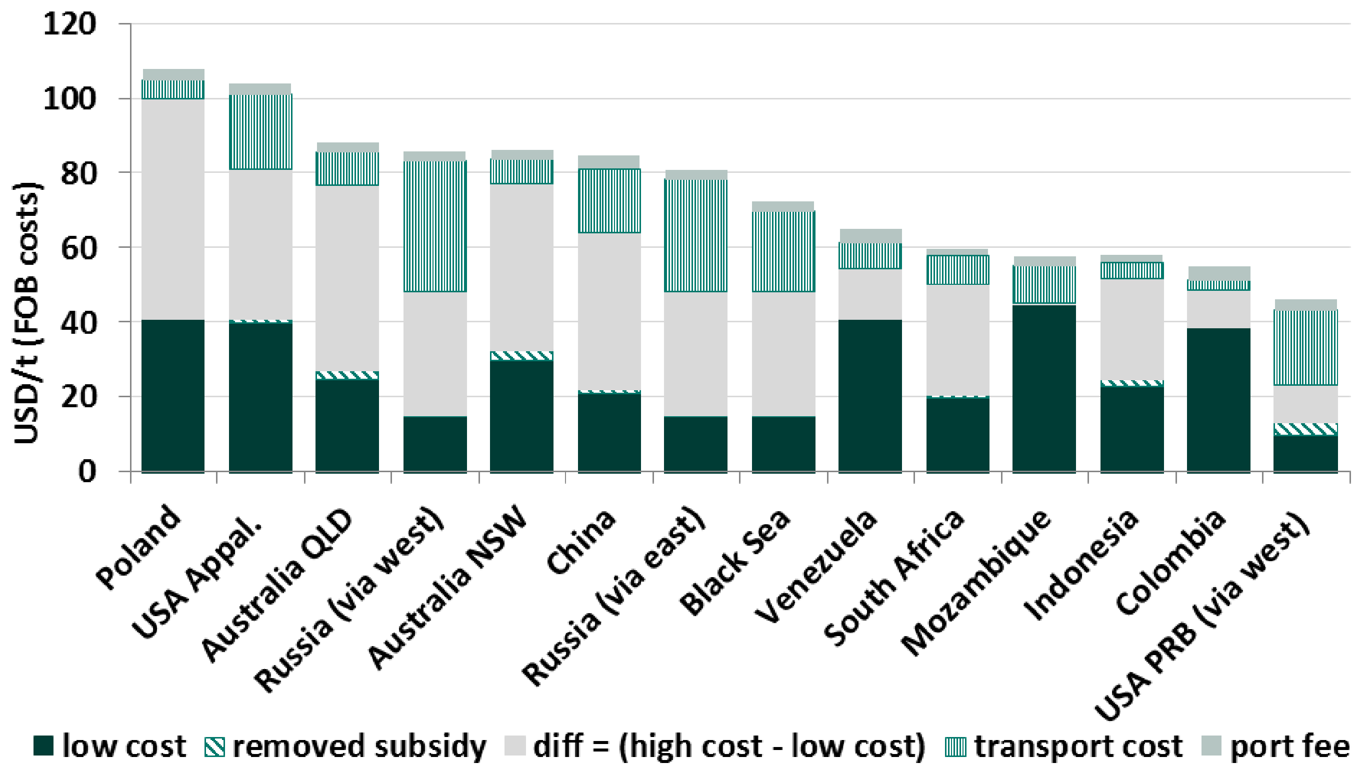
- Estimates vary: from 1-6.8bn USD in 2013
- Subsidy composition
  - relief of royalties (50%)
  - remediation (18%)
  - support for extraction (15%)
- Regional composition
  - federal (44%) vs state (54%)
  - Wyoming (Powder River Basin) state subsidies make up 50% of the total subsidy level
- Calculated subsidies:
  - Powder River Basin 3.4USD/t
  - Appalachia 1.1USD/t
  - All others 1.0USD/t

5 Coal Production Subsidies in China

- 5.8 bnUSD + 0.6-5.8 bn USD tax credits (1.5 to 3 USD/t of coal produced)
– subsidies for coal-bed methane, support for R&D, others
- Subsidy composition
  - direct payments and investments (54%)
  - provision of services below market value (39%)
  - foregone profits (6%)
- Regional composition
  - tax credit: state level (71%) and regional level (29%)
- Calculated subsidy level
  - 1.4 USD/t for producers from Shanxi, Shaanxi and Inner Mongolia
  - 0.9 USD/t for producer from all other regions
- 1 bnUSD share of the subsidies is compensations for the coal mines that are shut down in the coal phase-out plan.

→ Definition is non-specific on whether a subsidy is justified and efficient to remove market failures.

5 Supply-side policy: production subsidy removal has negligible effect on emissions



Subsidy definition based on Gerasimchuk et al. 2012

Markets reaction

- Price effect: 1% average increase compared to business -as-usual

Emissions reductions:

- 82 MtCO_2/a (equal to emissions from 15-16 large in coal-fired power plants)

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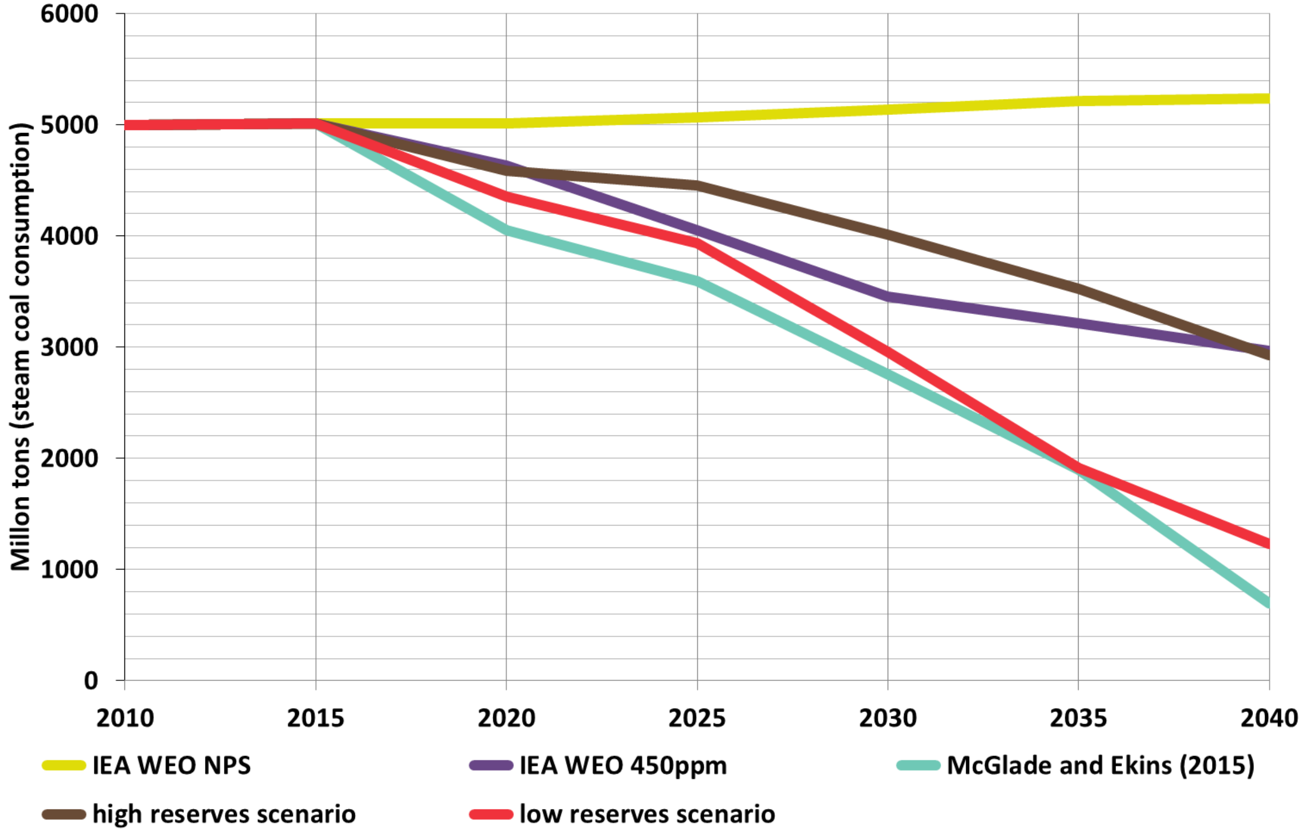
6 Estimate of coal resources, reserves, and reserves in operating mines

	BGR (2015)		Estimated Reserves in operating mines [Gt]
	Resources	Reserves	
Australia	1536.7	62.1	19.8
Colombia	9.9	4.9	3.2
China	5338.6	124.1	41.1 (85.2)
India	175	85.6	19.8 (48.4)
Indonesia	92.4	17.4	3.5
Kazakhstan	123.1	25.6	2.2
Mongolia	39.9	1.2	n.a
Mozambique	21.8	1.8	n.a
Poland	162.7	16.2	0.8
Russia	2658.3	69.6	17.7
South Africa	203.7	9.9	6.8
USA	6457.7	222.6	17.6
Ukraine	49	32	2.5
Venezuela	6	0.7	n.a
Vietnam	3.5	3.1	n.a
Total in data base	16878.3	676.8	135-207.7
World	17713.4	698.7	
Share of world total	95%	97%	

6

Supply-side policy: moratorium on new coal mines
Carbon content of operating mines exceeds CO_2 budget



Low reserves: 135Gt
with 41Gt in China and 20Gt in India

- Still not all reserves are mined
- 93% price increase relative to WEO NPS
- Seaborne trade concentrates on China and India

High reserves: 208Gt
with 85Gt in China and 48 Gt in India

- 33% price increase
- Very strong reduction in seaborne trade

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7 Main findings

Supply-side policies do not provide a one-fits-all solution to curb coal consumption

- **Removing producer subsidies can come with co-benefits of additional government funds but does not substantially reduce coal consumption**
- **A moratorium on new coal mines can be an important step to restrict future consumption but may be not enough . Moreover, it favors incumbents raises equity concerns**
- **Coal export/production taxes come with co-benefits of additional government funds but global coverage is required to achieve 2°C consistent consumption path**

Thank you for your attention.

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Back-Up

Supply-side policies

Demand-side vs. supply-side fossil fuel policies

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  - GHG accounting at the national level
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Supply-side fossil fuel policies: Collier and Venables (2014)

- sequential closure of the entire coal industry (compensated via ring-fenced cap-and-trade scheme for fossil fuel extraction)
- Provide argument for the formation of the coalition and combine economic incentives via a ring-fence cap-and-trade between oil and coal: medium cost coal is payed by oil industry to be conserved with moral pressure arguments

The essential insight is that moral pressure depends upon establishing a sequence of moral responsibility for closure decisions. At any one time, only a very few actors should bear the entire moral responsibility for action, but their compliance would trigger a reassignment of responsibility. To be accepted, the sequence must be perceived as fair, and this in turn must be derived from a moral context. This suggests a scheme in which coal producers agree to sequence closure, with high-income countries going first.

the production of coal is highly concentrated: it is largely conducted by only a few firms, employing a clearly identified group of workers, located in only a few countries.

the changes in the decisions by coal producers are major, they are readily observable.

Closing down the global coal industry meets the key features that give an action moral force. It is a concrete event, readily observable, and directly under the control of identifiable actors.

Carbon leakage effect

- Undisputed in its existence, but controversial in its magnitude.
- Ex-ante, the supply elasticity of coal is found to be crucial for the magnitude of the effect, with higher elasticity leading to stronger leakage effects (Burniaux and Oliveira Martins 2012).
- General Equilibrium frameworks
  - Felder and Rutherford, 1993; Paltsev 2001; Di Maria and Werf 2008: moderate rates of leakage
  - Babiker, 2005: High rates of carbon leakage; criticizes overly simplistic assumptions on market and industry structure
  - Arroyo-Currás et al., 2015: limited leakage of 15%, if the U.S., the EU and China act as pioneer regions.
  - Aichele and Felbermayr, 2015: ex-post empirical study of the effect of the Kyoto Protocol on GHG emissions, find a change in the production patterns of emission-intensive goods and thereby evidence for carbon leakage of about 8%
  - Combined with earlier findings by Aichele and Felbermayr (2012), the carbon leakage rate is estimated at roughly 40%.

Subsidy removal

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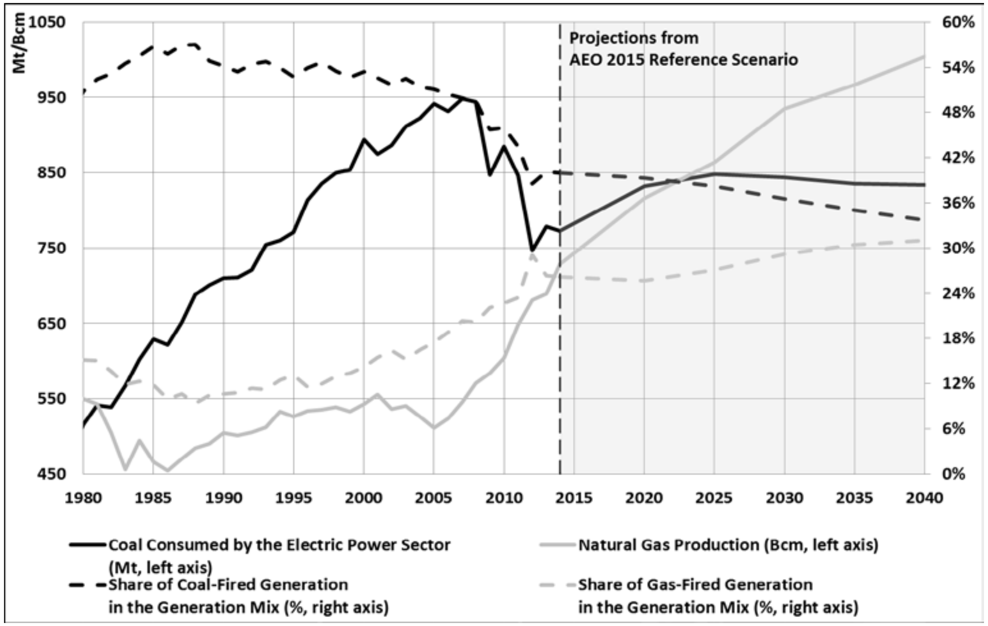
Key markets: United States

Major comedown of the U.S. coal industry:

- Steady decline in coal use over past decade, including in power generation
- Aging coal-fired power plant fleet (with 85% older than 30 years and 50% older than 40 years)
- 3 of the top 4 coal producers filed for bankruptcy by 2016, and 271 mines were idled or closed in 2013



Source: EIA 2015; EIA/DOE 2015

- Drivers of the comedown are:
  - Environmental regulation: Cross-State Air Pollution Rule (2011), Mercury and Air Toxics Standards (2012), Clean Power Plan (2014)
  - Decline of prices and demand due to cheap alternative in gas (share-gas revolution)
  - Prolonged opposition to export from Powder River Basin via Western States

Key markets: China

	Target year	Decrease in carbon-intensity of GDP	Share of non-fossil fuels in TPES	Comments
12th Five-Year Plan (2011)	2015	17% from 2011	11.4%	Decrease in energy-intensity of GDP: 16% from 2011
Action Plan on Prevention and Control of Air Pollution (2013)	2017			Share of coal in TPES: 65%
Energy Development Strategy Action Plan (2014)	2020		15%	Cap on coal consumption: 4200 Mt
National Plan on Climate Change (2014)	2020	40–45% from 2005	15%	
Intended Nationally Determined Contribution (2015)	2030	60–65% from 2005	20%	
Supply-Side Structural Reforms (2016)	2019-2021	Reduce coal production mine capacity by 500 Mt through direct regulation and by additional 500 Mt through reconstruction and consolidation; moratorium on approval of new mines		
"Promoting the orderly development of China's coal" Plan (2016)	2019	No approval of new coal-fired power station, halt for approved plants not yet under construction, scrappage of old inefficient plants before expiration of technical lifetime		

Findings from literature on coal production subsidies

Country	Total subsidies to coal production in 2013/14 [bn USD]	Subsidy per unit of production and by region [USD/t]	Comments
USA	2.1	Powder River Basin 3.4 Appalachia 1.1 others 1.0	Forgone profits due to preferential tax treatment account for 50%
China	4.4	Shanxi, Shaanxi, Inner Mongolia 1.3 others 0.9	Direct payments and investments, and the provision of services below market value account for 54%, and 39%, respectively.
India	0.8	all 0.9	Investment by SOE Coal India Limited

Source: various sources, mainly Global Subsidy Initiative (GSI), and International Institute for Sustainable Development (IISD)

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South Africa	0.04	transport to export terminal 0.5	Rail transport subsidy, below market value sales to preferential consumers already disregarded in base case data
Indone-sia	0.9	all 1.8	Policies targeting to remove subsidies are not enforced
Russia	0.07	0.4	Extreme divergence between sources on subsidy levels
Poland	0.01	0.1	Free energy supply for mine workers

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Moratorium on new mines

Estimate of coal resources, reserves, and reserves in operating mines

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Export/production tax

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   - Importing countries increase domestic production

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4 Case – Australian Export Tax

Tax Setter: Australia

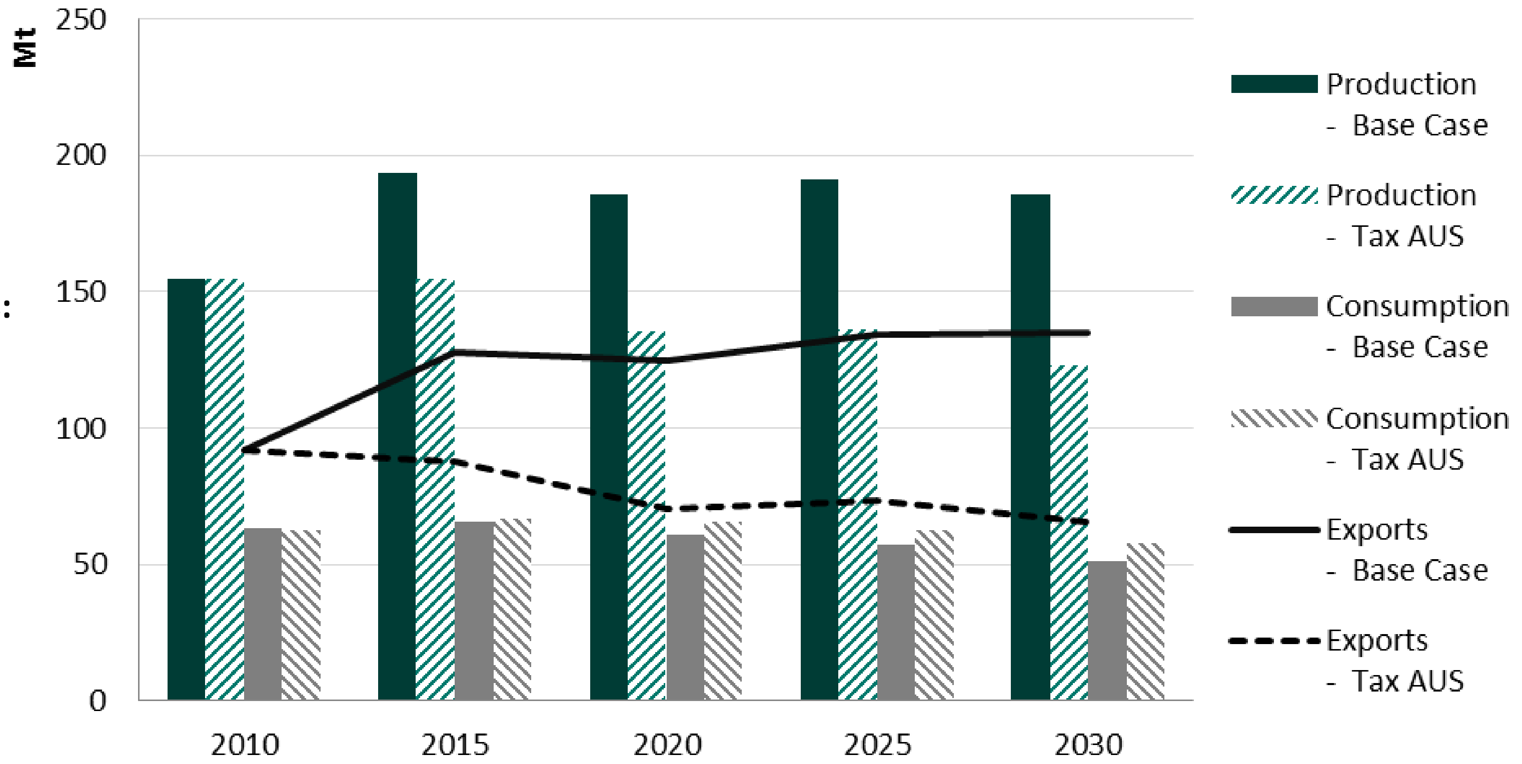
Tax Type: Export Tax

Discount Rate: 5%

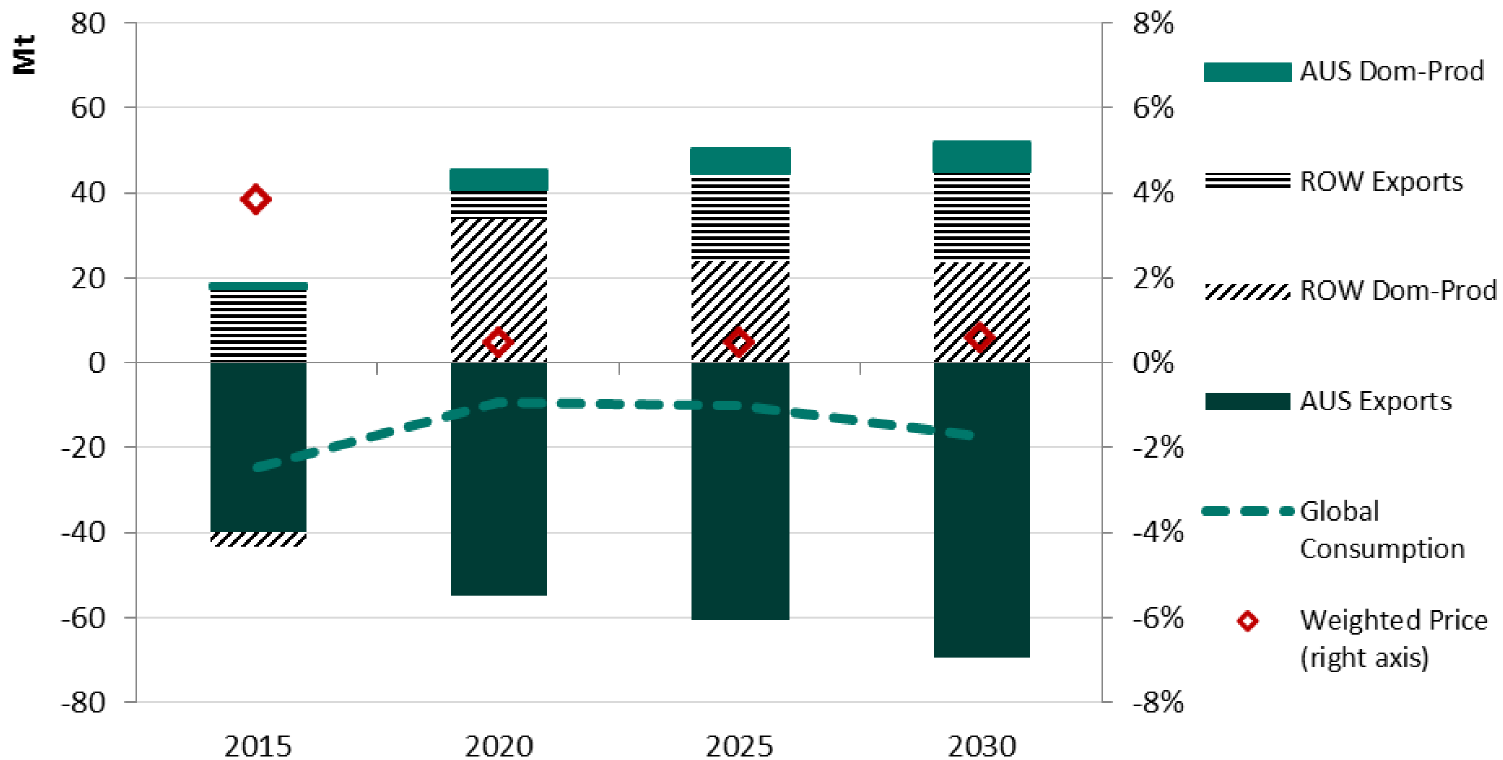
Annual growth rate of tax: 2.5%

Initial Tax Rate:
0.66 USD/GJ
(18 USD/ton of Australian coal, 6.7USD/tCO_2)

NPV Tax Revenues:
16 bn. USD



4 Case – Australian Export Tax - Global Impact



- Unilaterally reduced Australian production is largely compensated for (leakage of 70%)
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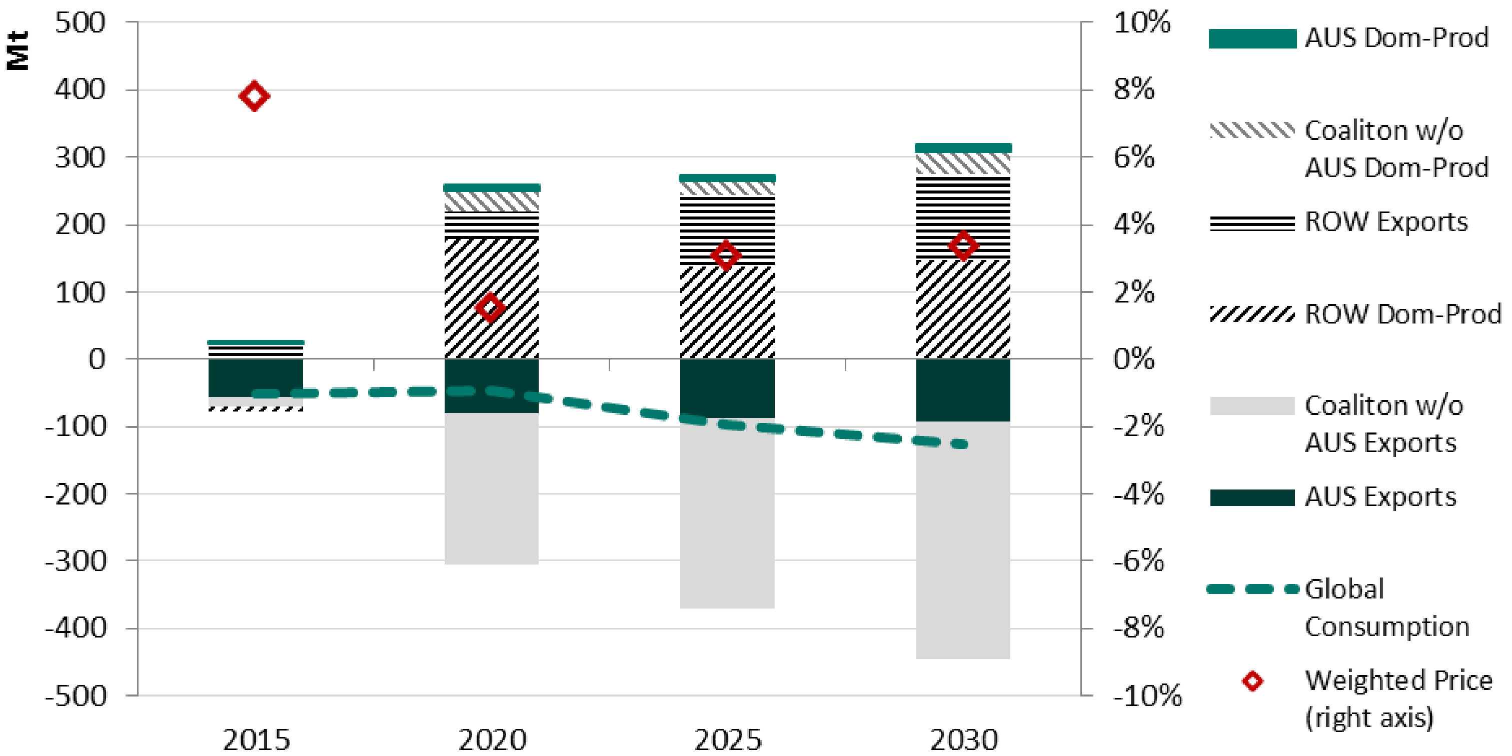


- Smaller leakage effect, larger reduction in global consumption
- Emissions reduced by on average 200 Mt CO_2 per year
- Significant price increase due to export tax

4 Case –Export Tax Coalition

Tax Setter: Australia, Colombia, Indonesia and South Africa

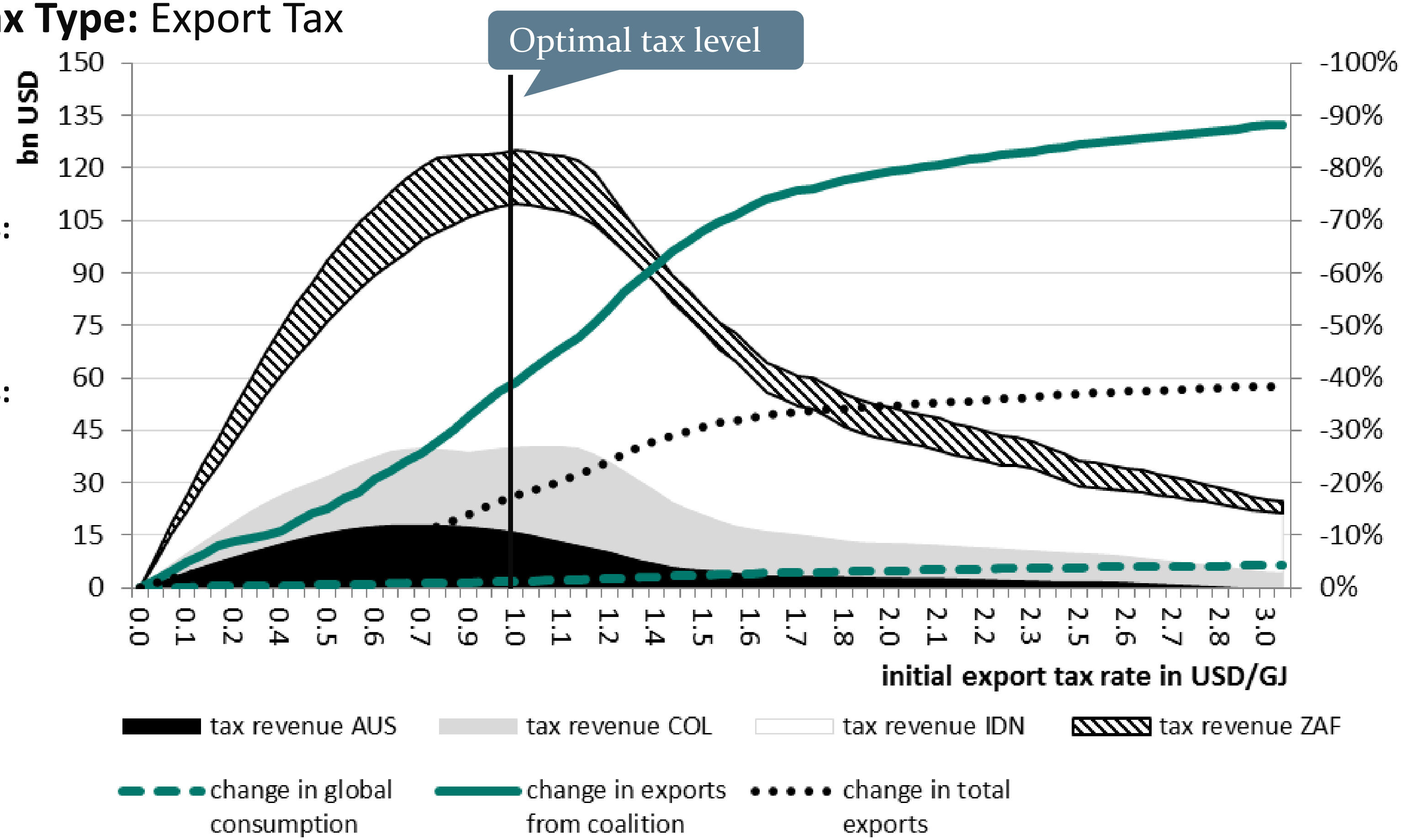
Tax Type: Export Tax

Discount Rate: 5%

Annual growth rate of tax: 2.5%

Initial Tax Rate:
0.99 USD/GJ
(10.1USD/tCO_2)
NPV Tax Revenues:
125 bn. USD

AUS
NPV Tax Revenues:
16 bn. USD

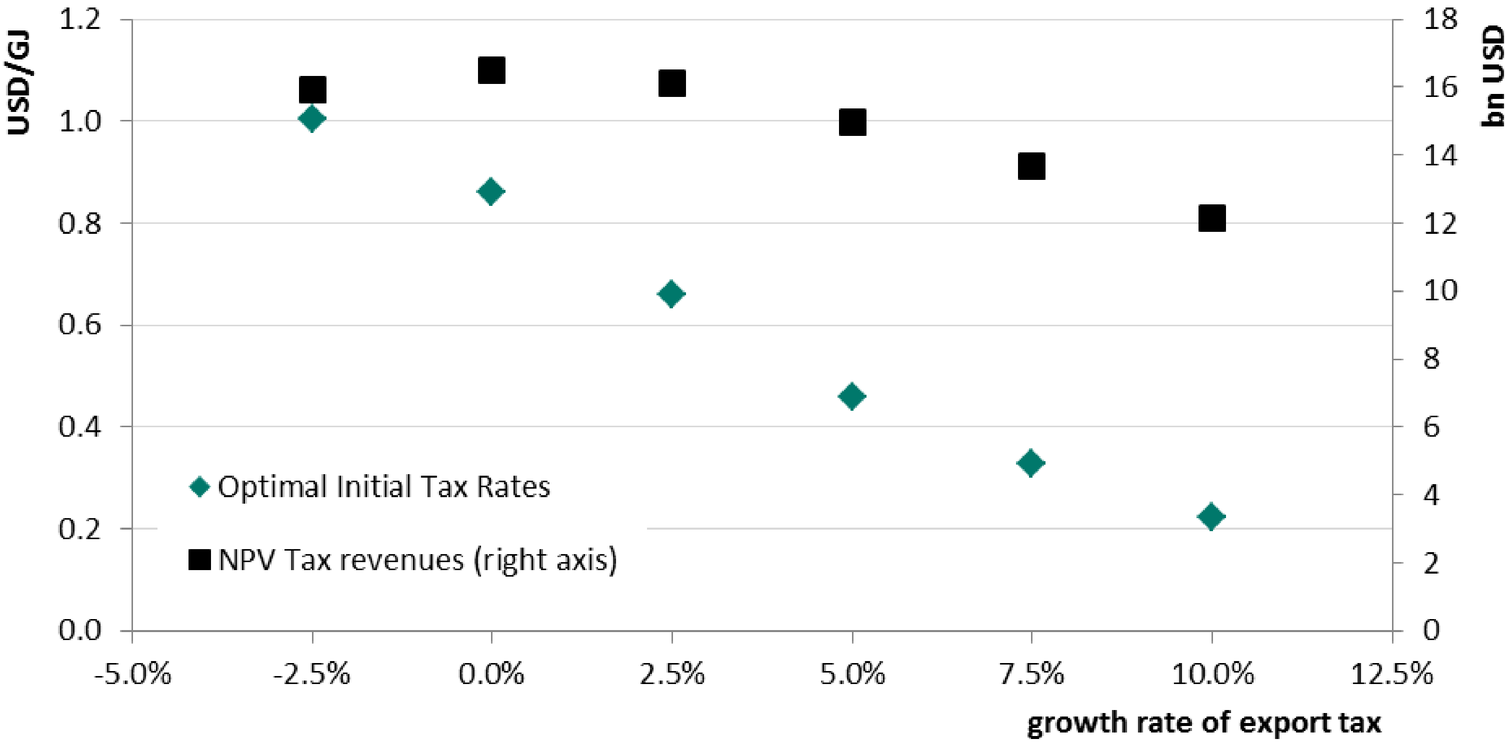


Case 1.1 – Australian Export Tax – Robustness Checks

Different discount rates:

- Relatively stable with same tax rates in a range of $r_g \in [0, 0.5]$

Different growth rates of the export tax:



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Case –Production Tax Australia

Tax Setter: Australia

Tax Type: Production Tax

Discount Rate: 5%

Annual growth rate of tax: 2.5%

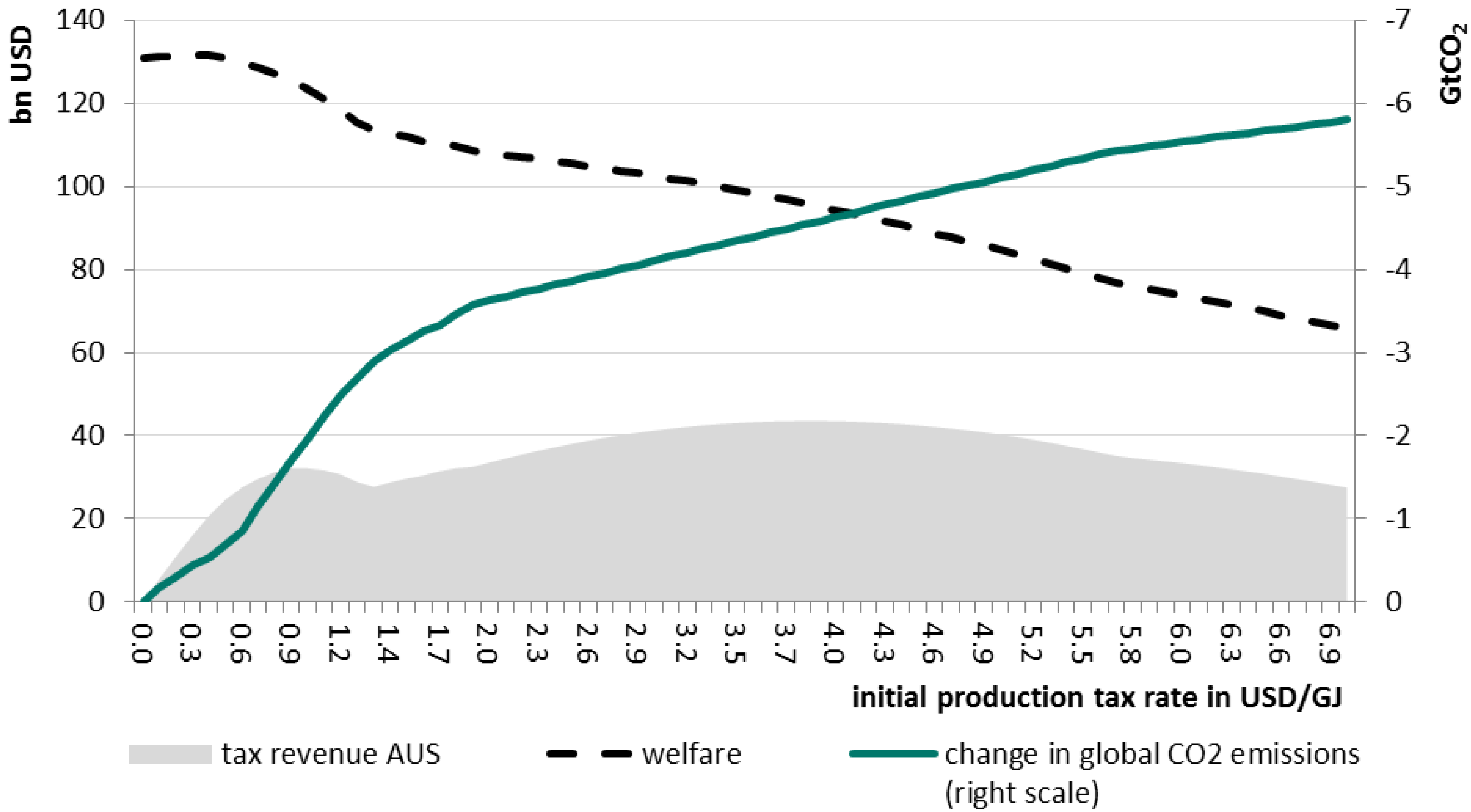


Figure: Time paths of the export tax rate and resulting tax revenues

Case –Export Tax Coalition with USA

Tax Setter: Australia, Colombia, Indonesia, South Africa, and **USA**

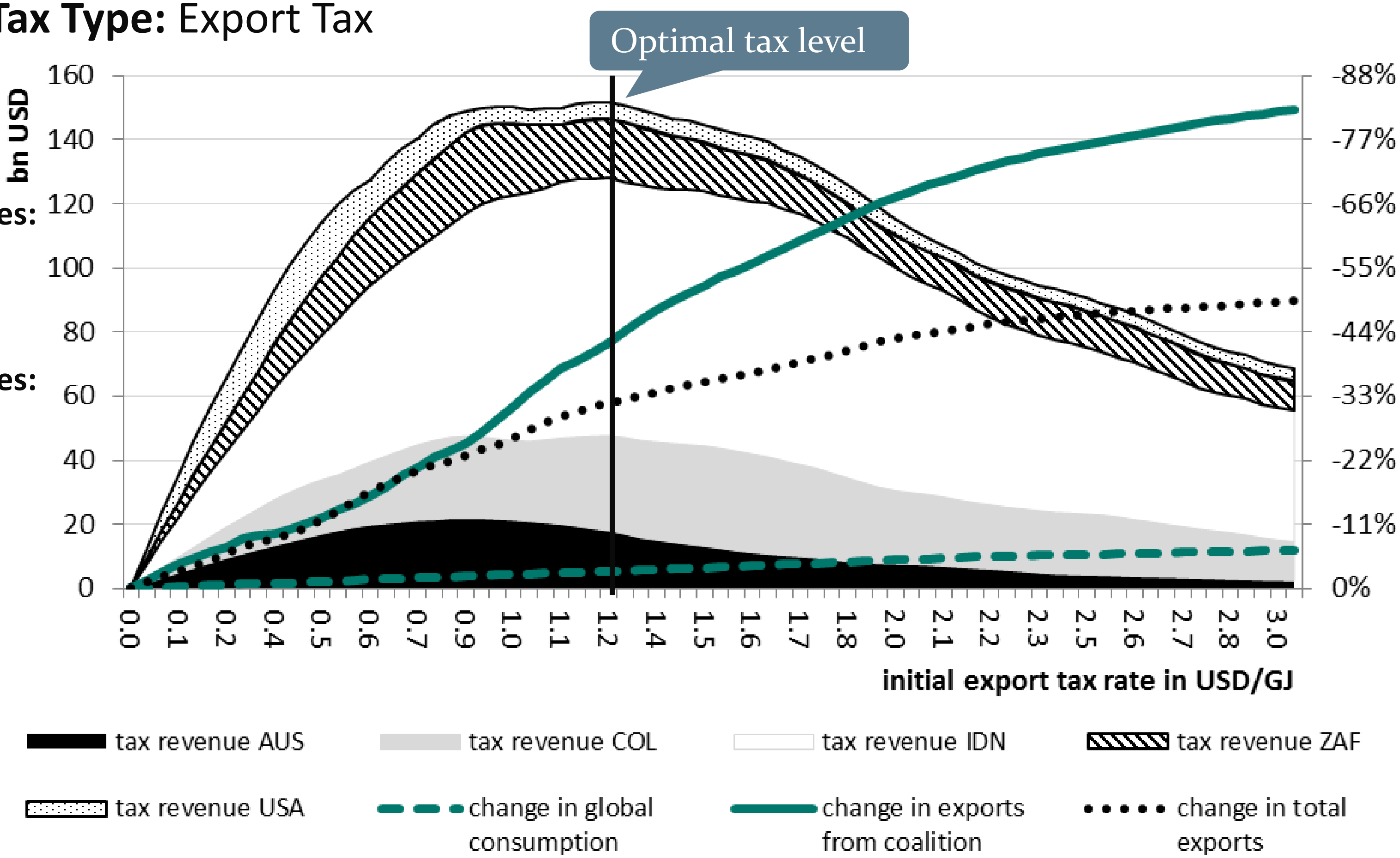
Tax Type: Export Tax

Discount Rate: 5%

Annual growth rate of tax: 2.5%

Initial Tax Rate:
1.23 USD/GJ
NPV Tax Revenues:
150 bn. USD

AUS
NPV Tax Revenues:
18 bn. USD



Case –Production Tax Coalition

Tax Setter: Australia, Colombia, Indonesia, and South Africa

Tax Type: Production Tax

Discount Rate: 5%

Annual growth rate of tax: 2.5%

Initial Tax Rate:
1.23 USD/GJ
NPV Tax Revenues:
266 bn. USD

AUS
NPV Tax Revenues:
36 bn. USD

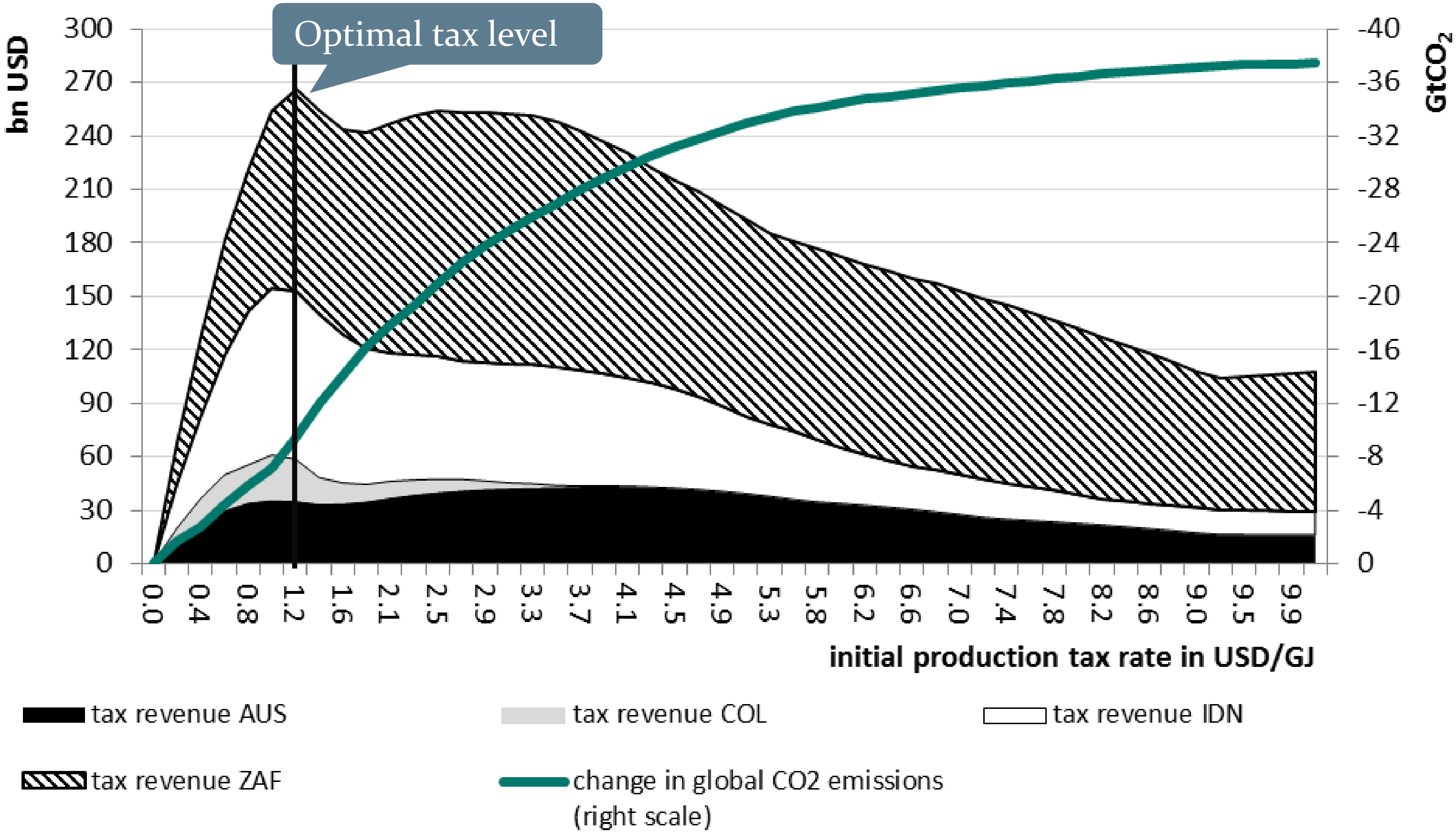


Figure: Time paths of the export tax rate and resulting tax revenues

2 Solution techniques for MPECs in GAMS and in literature

There exist different solution techniques for MPECs (with pros and cons)

- NLPEC GAMS solver
  - Lower level formulated by means of Karush-Kuhn-Tucker conditions as a Mixed Complementarity Problem (MCP)
  - Pro: fast solve   Con: only local optima
- Disjunctive Constraints in MILP formulation (Gabriel and Leuthold, 2010)

2 Disjunctive constraints formulation: exporters profit maximization problem

Exporters profit maximization problem:

$$\sum_{a\in A}\left(\frac{1}{1+r_e}\right)^a \cdot \Pi_e^E(z_{aec};inv_{ae}^E)=\sum_{a\in A}\left(\frac{1}{1+r_e}\right)^a \cdot \begin{pmatrix} \sum_c p_{ac}^C \cdot z_{aec}-\sum_c p_{ae}^E \cdot z_{aec}-\sum_c fee_{ae}\cdot \kappa_e \cdot z_{aec} \\ -\sum_c \cdot searate_{aec}\kappa_e \cdot z_{aec}-Cinv_{ae}^E \cdot inv_{ae}^E-\tau_a^E \cdot z_{aec'} \end{pmatrix}$$

s.t. $\overrightarrow{constraints}\perp\vec{\lambda}\geq 0$

Initial KKT condition for z:

$$0\leq\left(\frac{1}{1+r_e}\right)^a \cdot\frac{\partial\Pi_e^E(z_{aec};inv_{ae}^E)}{\partial z_{aec}}+\frac{\partial\left(\vec{\lambda}\cdot\overrightarrow{constraints}\right)}{\partial z_{aec}}\perp z_{aec}\geq 0$$

Rewrite the lower level:

Replace complementarity conditions by disjunctive constraint,

$$0\leq\left(\frac{1}{1+r_e}\right)^a \cdot\frac{\partial\Pi_e^E(z_{aec};inv_{ae}^E)}{\partial z_{aec}}+\frac{\partial\left(\vec{\lambda}\cdot\overrightarrow{constraints}\right)}{\partial z_{aec}}\leq bin_{aec}^z \cdot K_{aec}^z$$

$$0\leq z_{aec}\leq(1-bin_{aec}^z)\cdot K_{aec}^z$$

where K^z is a sufficiently large number to ensure the complementarity.

2

Disjunctive constraints formulation: linearized objective function

Initial objective function:

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

Reformulatethe objective function:

- Define a set d of exogenous tax rates
- Introduce auxiliary variable
- Relate them to binary variables

$$rev_d \leq \sum_{aec'} \left(\frac{1}{1+r_g} \right)^a \cdot \tau_{a,d}^E \cdot EXP_{aec'} \qquad \Rightarrow \qquad obj = max \sum_d rev_d$$

$$rev_d \leq K_d^\tau \cdot bin_d^\tau$$

$$\sum_d bin_d^\tau = 1$$

- The optimal tax rate (of given ones) is chosen by setting the value of one binary variable to unity

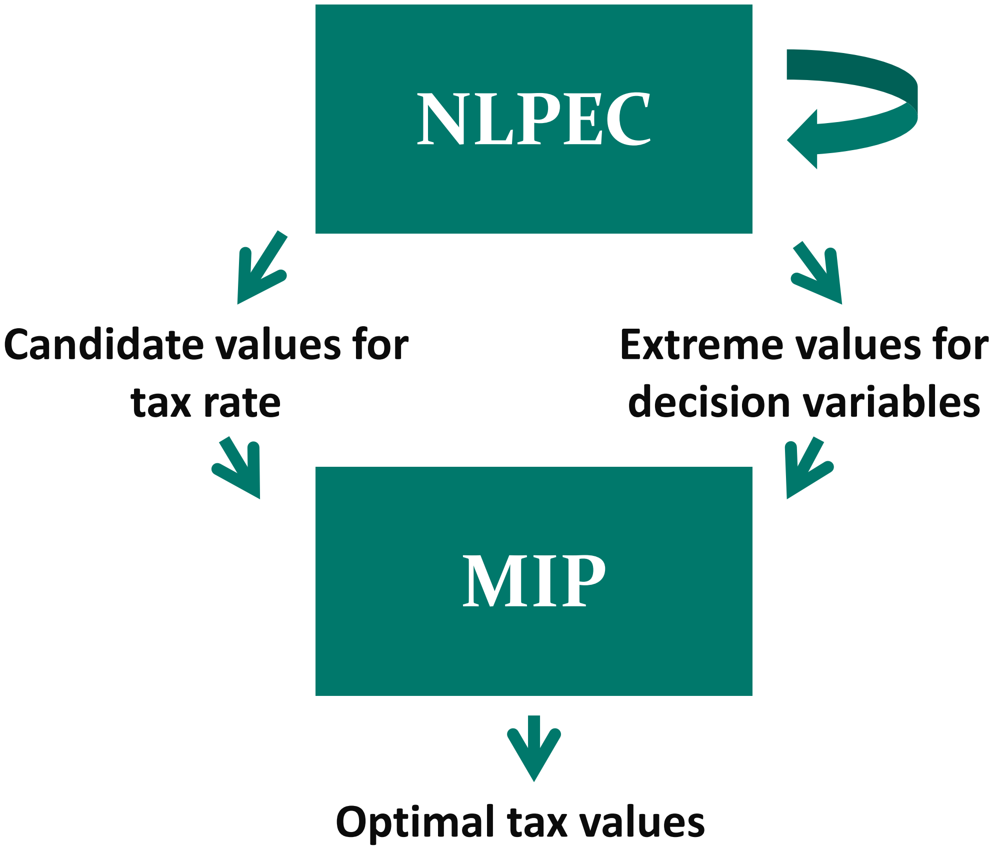
Solution techniques for MPECs in GAMS and in literature

There exist different solution techniques for MPECs (with pros and cons)

- NLPEC GAMS solver
  - Lower level formulated by means of Karush-Kuhn-Tucker conditions as a Mixed Complementarity Problem (MCP)
  - Pro: fast solve   Con: only local optima
- Disjunctive Constraints in MIP formulation (Gabriel and Leuthold, 2010)
  - Conversion of complementarity conditions to disjunctive constraints (binary variables plus large numbers)
  - Discretized tax rate to avoid bilinear term (tax*quantity)
  - Pro: global optimum   Con: choice of large numbers, discretized tax

Approach to solve the large-scale MPEC

Task: Find optimal tax rate level that maximizes total discounted tax revenues subject to a competitive market equilibrium



- Insert model in two level format
- Run loop with different upper and lower bounds for continuous tax rate
- Obtain different local optima as candidates for global optimum

- Reformulate lower level with disjunctive constraints
- Calculate BIG K based on extreme values
- Construct interval around candidate global maximum
- Solve MIP to confirm 'global' optimality

Back-Up

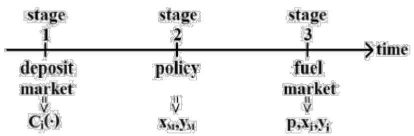
COALMOD-World

Supply-side fossil fuel policies: Harstad (2012)

- Coalition of the willing buys high-cost coal deposits and conserves them
- The coase theorem is applicable because a market for extraction right exists, property rights are well defined, and transaction costs are moderate…
  - M countries participate in climate treaty (M treated as one country),N countries do not, N do not take the harm from fossil fuel production into account

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) \quad \text{if } i \in N,$$

$$U_i = B_i(y_i) - C_i(x_i) - p(y_i - x_i) - H\Big(\sum_{M \cup N} x_i\Big) \quad \text{if } i = M,$$



  - 1. There is a market for fossil fuel deposits (they are ranked according to a marginal supply cost curve C(.))
  - 2. Coalition sets policy through quotas (xm,ym), invariance between quota and tax if uncertainty is not accounted for (Weizman 1974)
  - 3. fuel market clears with p, xi,yi
- Results
- To reach the first best, the above results state that all “marginal” forests with a conservation value must be preserved. One should thus pay to protect the areas that are just barely profitable to log, as well as those areas that would become profitable once the REDD policy is implemented and the timber price has increased.
- Harstad ignores the coalition’s incentive to delay paying for conservation (Harstad 2012b).
- A country may own unknown or potential deposits, and with some effort it can determine whether these contain fossil fuel. Since the incentive to search for new deposits is stronger if the fuel price is high, countries may search more if there is a deposit market. The effort to search is then suboptimally high since a nonparticipant does not internalize the environmental consequences if a new deposit is detected and exploited. Coalition would pay nonparticipants for not searching.
- nonparticipants will invest too much in reducing their extraction costs unless the coalition can discourage such investments.

Mathematical Formulation
A Producer's Optimization Problem

Each producer f maximizes its discounted profits …

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

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

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

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

where marginal costs increase in accumulated extraction via:

$$mc\_int_{af} = mc\_int_{(a-1)f}$$

$$+mc\_slp_{(a-1)f} \cdot \kappa_f \cdot mc\_int\_var_f \cdot \left(\sum_c x_{(a-1)fc} + \sum_e y_{(a-1)fe}\right)$$

Mathematical Formulation:
A Exporter's Optimization Problem

Each exporter e maximizes its discounted profits …

$$\max_{z_{aec},\, inv^E_{ae}} \Pi_e = \sum_a \left(\frac{1}{1+r_e}\right)^{a-1} \cdot \left[\sum_c p^C_{ac} \cdot z_{aec} \right.$$
$$\left. - \sum_c \left(p^E_{ae} \cdot z_{aec} + fee_e \cdot \kappa_e \cdot z_{aec} + sea_{aec} \cdot \kappa_e \cdot z_{aec} + \tau^E_a \cdot z_{aec'} \right) - Cinv^E_{ae} \cdot inv^e_{ae} \right]$$

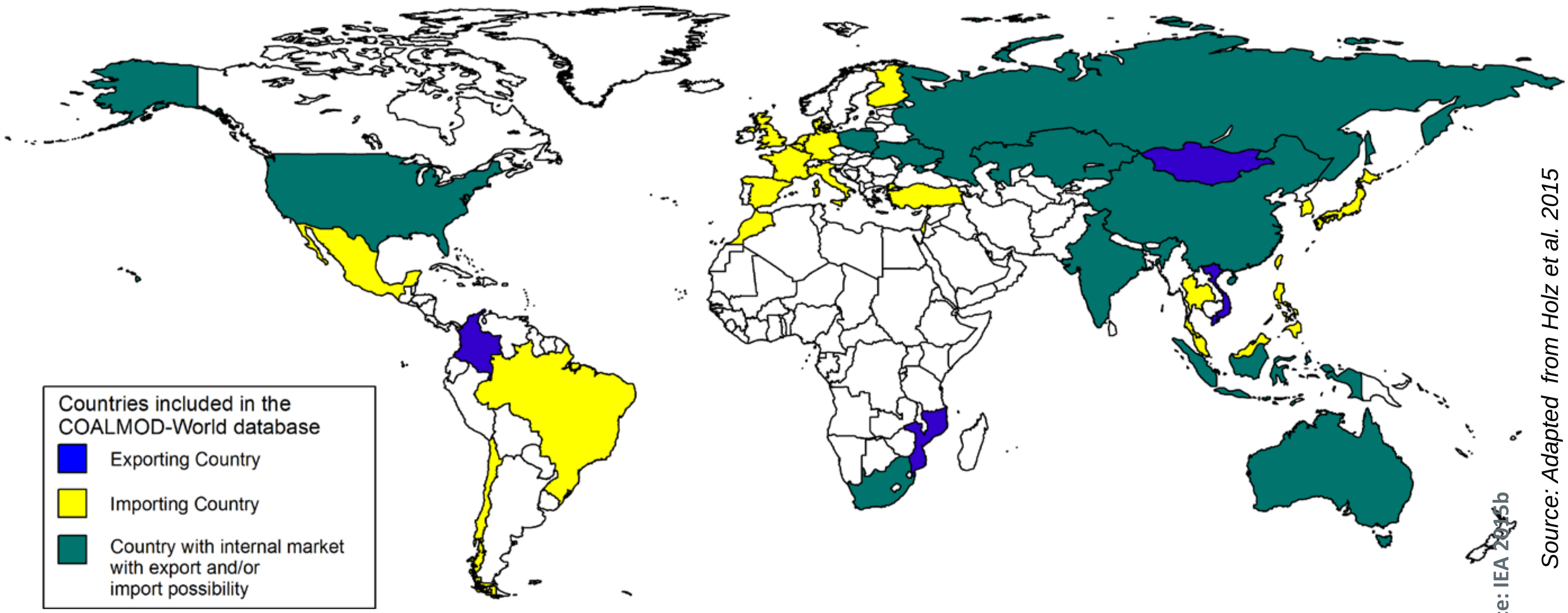
s.t. to constraints:

- maximum export capacity constraint
- maximum annual investment in export capacity constraint

Market clearing:

- Mass balance between producers and designated exporters
- Producers/exporters and consumers clear via an inverse demand function

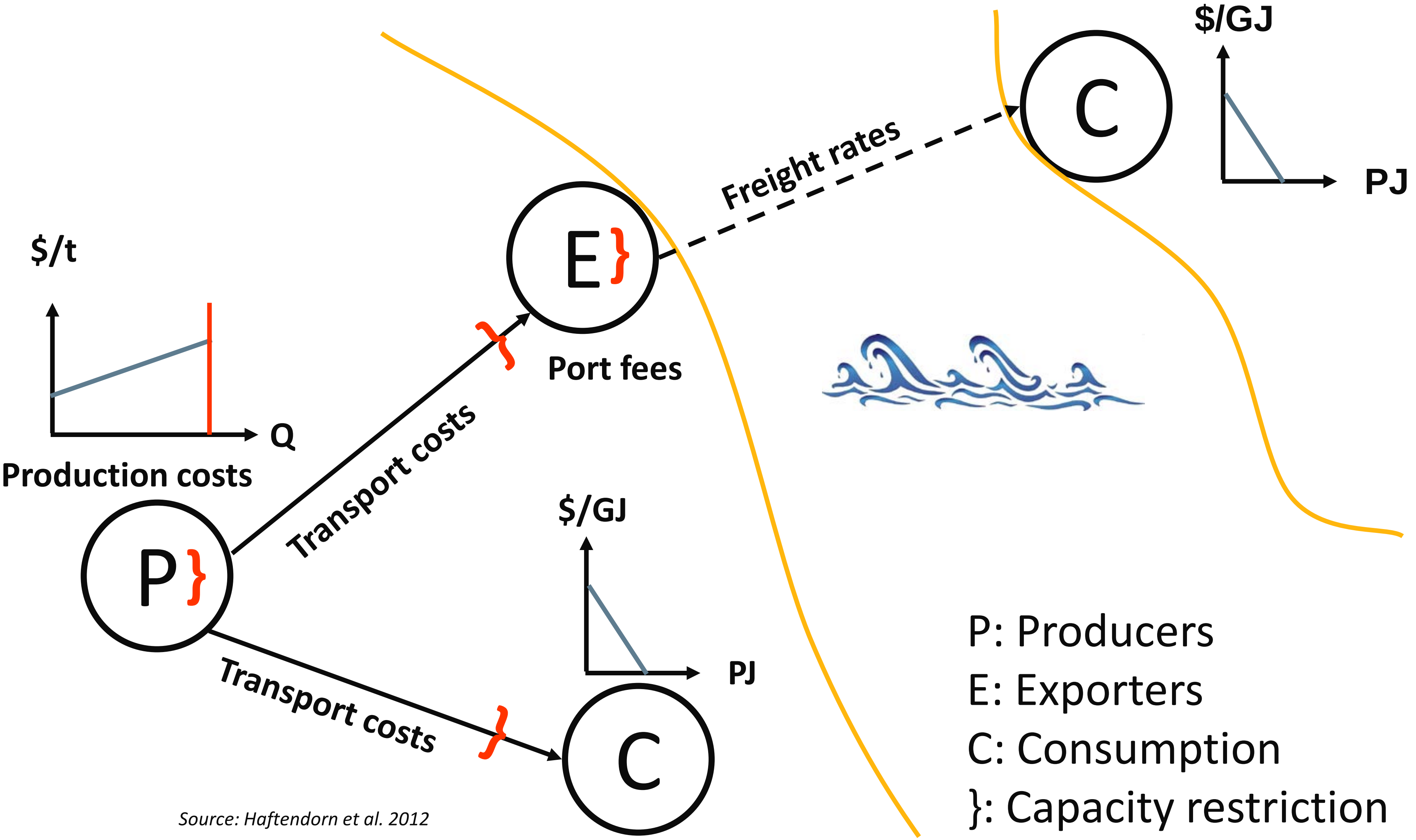
Quantitative assessment using COALMOD-World



Equilibrium problem

- Large-scale multi-period equilibrium model of a competitive steam coal market (modeled as MCP) initially developed by Haftendorn et al. 2012 and Holz et al. 2015
- Profit-maximizing players with specific constraints
- Market clearing via inverse demand functions
- Endogenous investment in production and export capacities
- Substitution between importing and domestic production

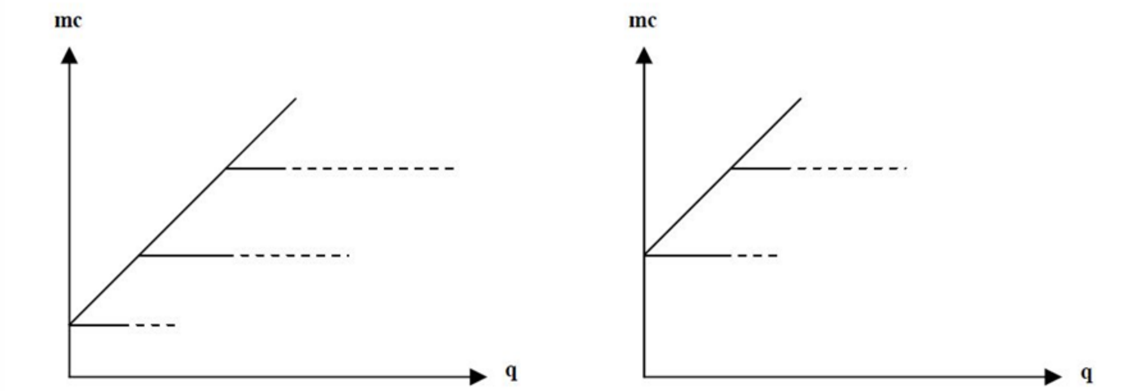
Structure of COALMOD-World



P: Producers
E: Exporters
C: Consumption
}: Capacity restriction

Source: Haftendorn et al. 2012

Mine mortality mechanism



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

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

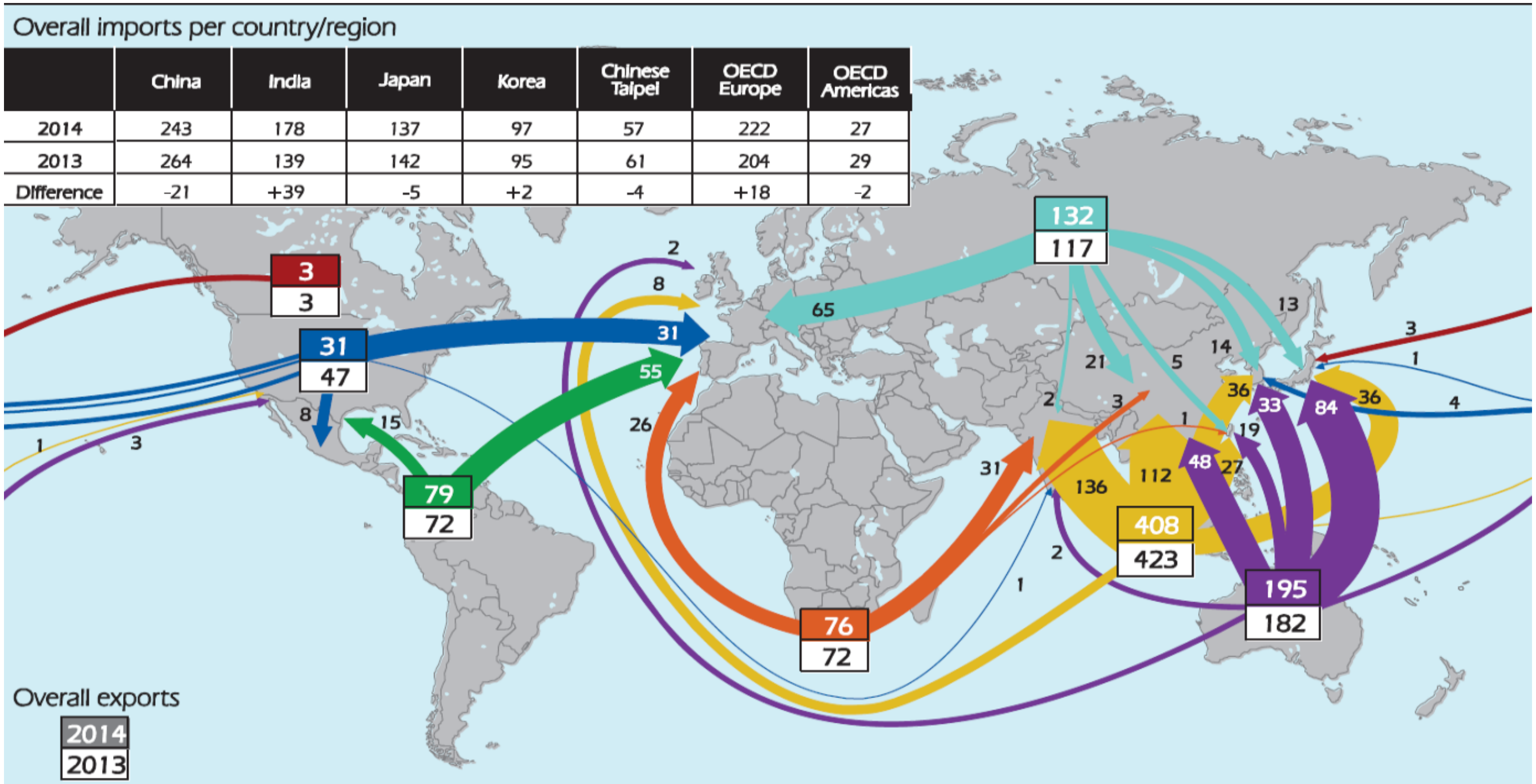
Production cost: static → specific mine operates at constant marginal costs

- horizontal line: production capacity in one period + dashed line = reserves of a mine
- aggregated cost curve in one period: add production capacities on the q-axis and connect them with their respective marginal costs on the mc-axis

Production cost: over time → all mines may produce coal in one period but cheapest mines are depleted first

- cheapest mines are mined out
- cheapest producer disappears from the cost curve ("mine mortality") → intercept increases
- "mine mortality ~1 → means that the cumulated production leads to a complete depletion of the oldest, cheapest mines → mature and old mining basins.
- "mine mortality ~0 → mines situated on the low cost segment of the basin's cost curve still have significant reserves and will only be depleted in the mid- to long term
- slope of the cost curve indicates the relation of cheap and more expensive mines → slope is the second factor in determining the new intercept's position

Overview of world steam coal market: supply, demand, trade



	China	India	Japan	Korea	Chinese Taipei	OECD Europe	OECD Americas
2014	243	178	137	97	57	222	27
2013	264	139	142	95	61	204	29
Difference	-21	+39	-5	+2	-4	+18	-2

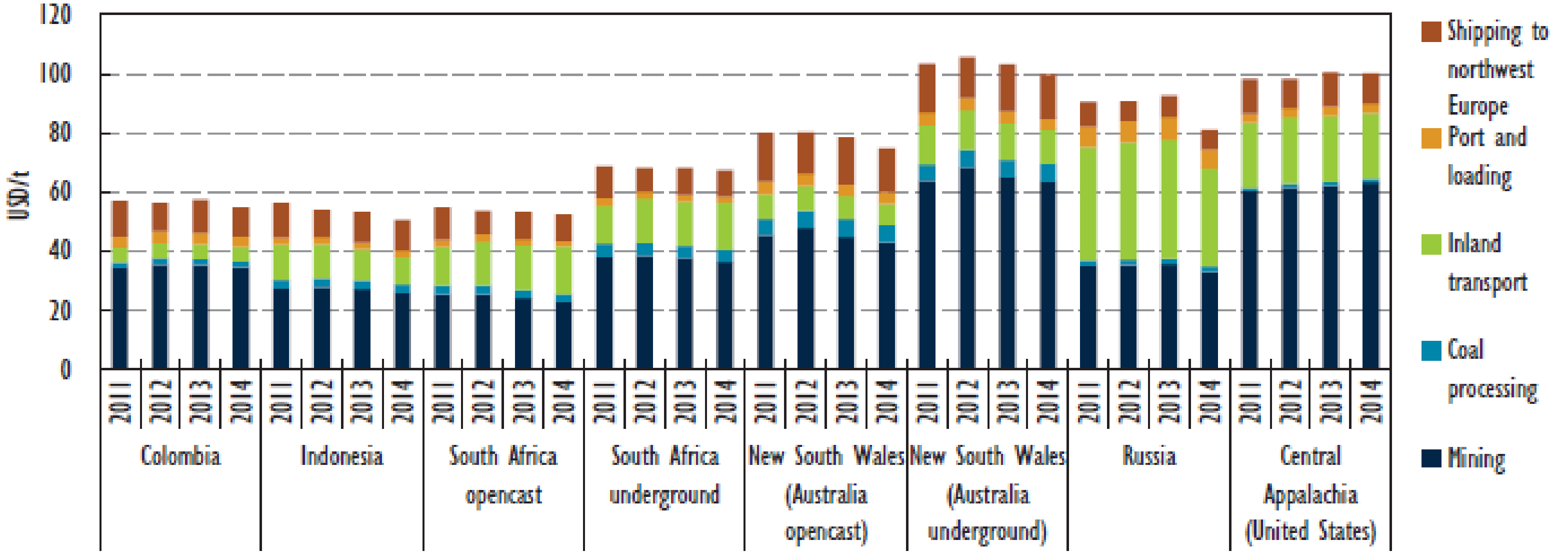
Source: IEA 2015b

Major producers in 2014
- China (3,200 Mt)
- United States (770 Mt)
- India (560 Mt)
- Indonesia (470 Mt)
- **World production 6,150 Mt**

Major consumers in 2014
- China (3,280 Mt)
- India (760 Mt)
- United States (750 Mt)
- **World consumption 6,090 Mt**

Source: IEA 2015c.

Price formation



Source: IEA 2015b

- Capital costs of coal production are relatively small, variable costs more significant
- Costs will range between regions, especially based on the distance to market
- Price formation is fundamentally based on the variable costs, freight rates and the exchange rate – but will also depend on whether a buyer's or seller's market prevails