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Coal's Medium-Run Future Under Atmospheric Greenhouse Gas Stabilization

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Abstract We assess the future of coal under alternative climate stabilization regimes, investigating how the quantity and location of future coal production, trade and use depends upon five factors: the supply-side constraint of resource depletion, diversification and deepening of international trade, economic growth, trends in energy intensity, and the availability of coal-fired carbon-free electric generation technology (IGCC-CCS). Using the *Phoenix* computable general equilibrium model of the world economy, we find that coal is sensitive to demand-side assumptions about economic growth and energy-saving structural or technological change. In a 550 ppm stabilization emission tax scenario, the gobal coal industry initially declines sharply and then rebounds, in 2050 reaching roughly the same size as it is today—but only if IGCC-CCS is available by 2020. Under alternative stabilization regimes, IGCC-CCS penetration is a key influence on production and imports in major coal regions, where it interacts with extraction costs driven by the rate of depletion relative to trade partners.

Keywords energy production · energy use · trade · coal · computable general equilibrium · CO_2 emissions

1 Introduction

Coal is an abundant and relatively inexpensive energy resource that accounted for 27% of world primary energy in 2010 (IEA, 2012). It is also the most carbon-intensive fossil fuel, responsible for 44% of the world's energy-related carbon-dioxide (CO_2) emissions (EIA, 2013). In a "business as usual" (BAU) future

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without international climate policy, economic expansion is expected to stimulate increases in the demand for energy generally—and coal in particular (EIA, 2013). How much coal is used in the future, and the regions where is it produced and consumed, are determined by the critical structural factors of (1) supply-side constraints of resource depletion, (2) diversification and deepening of international trade, and demand-side changes in (3) economic growth and (4) sectoral input intensities.

The possible emergence of an international policy architecture in which nations undertake coordinated actions to stabilize atmospheric greenhouse gas (GHG) concentrations adds further influences to the mix. Climate change mitigation measures will likely increase the costs of using fossil fuels in proportion to the latter's GHG intensities. The impact will be a substantial reduction coal demand, production and exports as firms and households substitute toward relatively cheap non-energy inputs for more expensive energy, and less GHG-intensive energy supplies such as renewables or natural gas, with the pace of coal's exit being directly tied to the stringency of the international policy regime. The major offsetting factor is technological progress that preserves the use of coal in spite of the exigencies of GHG abatement requirements. A pivotal factor (5) is technological innovation to bring CO_2 capture and storage (CCS) to scale, which in conjunction with integrated gasification combined-cycle (IGCC) or natural gas combined-cycle (NGCC) electric power generation enables continued burning of fossil fuels to meet electricity demands with negligible net release of CO_2 to the atmosphere. Coal used by IGCC-CCS is therefore exempted from policies such as GHG taxes, sustaining demand.

In this article we investigate the impact of the aformentioned five factors within the context of the Energy Modeling Forum (EMF) 27 study, focusing on the evolution of coal production and trade at the global and regional levels to the year 2050. *Phoenix*, a dynamic multi-region, multi-sector computable general equilibrium (CGE) simulation of the world economy, is used to make projections of the international coal market under a BAU scenario and with harmonized international emission tax policies for stabilizing atmospheric GHG concentrations at 550 ppm and 450 ppm CO_2 equivalents by the year 2100, both with and without the availability of CCS technology. In this respect our analysis is similar to McFarland et al (2009), but places less emphasis on either the modeling of CCS and conventional electricity generation technologies or the effects of differing assumptions on the availability of competing energy resources such as natural gas and nuclear, in order to focus more sharply on the structural drivers of future coal production and trade.

We find that, by the year 2050 under the BAU scenario and with our baseline modeling assumptions global coal production and exports both nearly triple, with shifting regional production shares that are fundamentally driven by differences in rates of resource depletion. Out of the five factors identified above, our projections are most sensitive to assumptions about regions' economic growth rates, and, to a lesser extent, energy-saving structural and technological change. Stabilizing atmospheric GHG concentrations by levying a tax on CO_2 emissions that increases over time generates declines in global and regional coal extraction which, although initially large and sudden, does not continue, and is instead followed by a stagnation and slight increase in production which is more pronounced when CCS technology is available. Even with our more stringent emission taxes under a 550 ppm stabilization scenario the world coal industry in 2050 is the same size as today, but only with IGCC-CCS. Compared with production, a global emission tax prompts a much smaller change in aggregate coal exports from the BAU. Under GHG stabilization, coal imports by the key coal consumers China/Taiwan and India increase relative to their BAU levels, driven by the expansion of demand for coal by IGCC-CCS electric generation. This technology is significantly more important for electric power production in these regions than in the U.S., whose exports of coal to China/Taiwan and India increase.

The remainder of the paper is organized as follows. Section 2 begins by outlining the ways in which the factors above are manifested within the types of simulation models used to assess energy and climate change policies. Building on these insights, Section 3 describes numerical experiments with the *Phoenix* model that are designed to characterize energy market responses to these factors. Section 4 presents and the results of these simulations at the global and regional levels. Section 5 offers a summary and concluding remarks.

2 The Global Coal Market: Key Influences and Their Representations Within Models

We consider five factors which influence the evolution of global coal markets: resource depletion, diversification of imports supplies, economic growth, energy-saving structural change, and the adoption of CCS technology under emission constraints. In this section we discuss both their effects and their representation within economic models used for climate policy analysis.

2.1 Resource Depletion

The future trajectory of global fossil fuel supply is fundamentally determined by the race between depletion of the resource base and technological improvements in extraction. Following Rutherford (1998), production of fossil fuels has been modeled using a CES cost function in which reproducible inputs substitute for a non-reproducible “fixed factor” which represents the natural resource. Given the resource’s benchmark share of production costs, the elasticity of substitution can be chosen to mimic the elasticity of an upward-sloping supply curve which is thought to plausibly represent the depletion-innovation tradeoff over the long run.[1] This formulation is well suited to capture fossil fuel producers’ expansion of output—increasing extraction effort by purchasing more reproducible inputs, thereby driving up the marginal cost of production. Increased production also drives up the shadow price of the resource, and if this occurs faster than the increase in the output price the resource share of production cost rises as well, reducing the elasticity of supply (Boeters and Bollen, 2012).[2]

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[1] The supply elasticity is given by $\eta = \frac{1-s}{s}\sigma$, where s is the share of the natural resource in the cost of production and σ is the elasticity of substitution between the resource and reproducible inputs to the extraction sector.

[2] The key assumption driving this behavior is a less-than-unitary elasticity of substitution between reproducible inputs and the resource, which would seem to make sense given that the latter is a necessary input to production.

We implement a variant of this procedure in *Phoenix*'s coal, crude oil and natural gas sectors, where reproducible inputs are modeled as a nested CES composite of intermediate commodities, labor and capital. The model solves for the optimum short-run quantity of extraction which equalizes both the cost of the marginal exajoule of fossil fuel in each region with the computed price in domestic and overseas markets, and the marginal revenue of fossil fuel sales with the opportunity cost of the cost-minimizing combination of inputs necessary for extraction. A limitation of the standard approach in the previous paragraph is its inability guarantee that the increase in production cost will be sufficient to constrain cumulative energy extraction to be consistent with a resource base of a particular size. *Phoenix* imposes this constraint via a depletion penalty on the productivity of the coal, oil and gas sectors. The model records the energetic content of both the resource base and the quantity of production in each period, and depletion by decrementing the former in a declining balance calculation. The decline in the available resource over time then reduces the productivity of the three sectors, with each percentage-point decrease in available resources recursively generating the same reduction in the productivity of *all* inputs to production in the succeeding period. The magnitude of this depletion penalty depends on the rate of production relative to the size of the resource base. Depletion-driven productivity declines will be small in regions whose resource bases are large relative to their current production, and less likely to constrain increases in coal production and exports over the short to medium term. By contrast, regions where production is large relative to the resource base face more rapid depletion and declining resource productivity, with attendant reductions in output and exports.

2.2 International Trade: Market Deepening and Diversification

Coal is a heterogeneous substance whose quality (energy content and attributes—ash and potential pollutants such as sulfur) can vary substantially within individual coal-bearing formations, not to mention across large coal-producing areas of the world (EIA, 2013, p. 85). It is therefore unrealistic to model coal exported from different regions as a homogeneous good traded at a single price (the Heckscher-Ohlin (H-O) formulation); its character is more consistent with the assumption of differentiated regional varieties that underlies Armington's (1969) model of international trade, which has long been a mainstay of multiregional economic models. *Phoenix* simulates international trade using the CES/H-O and CES/Armington formulations. Domestic and imported goods are assumed to be imperfect substitutes that differ in price, which is modeled by representing sectors' and households' total uses of each commodity as CES composites of domestic and imported varieties. Crude oil and natural gas are the lone H-O commodities.[3] Exporters of these goods supply a global pool at a single world price, from which regional import prices differ by the amount of trade and transport margins. Coal and other

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[3] In the case of natural gas, trade is a small but rapidly-expanding share of global demand, doubling in volume over the last decade (EIA, 2013, p. 56). While pipeline flows account for the majority of gas exports, the continuing growth of liquefied natural gas (LNG) terminal capacity and tanker flows suggest the development of a future international market with the depth and flexibility to arbitrage regional price differences. In anticipation of such a market, gas is treated as an H-O good in *Phoenix*.

goods are Armington commodities, with every region's total imports modeled as a CES composite of varieties that correspond to individual trade partners. This formulation's usefulness is that it facilitates tracking of the different quantities of energy embodied in the coal traded by various regions.[4]

The practical implication is that while simulated trade in oil and gas is constrained only by *global* supply, coal movements are restricted to pairs of regions that possess bilateral import-export linkages in the model's benchmark dataset—over the course of the simulation "locking out" regions that do not initially trade with each other. This is a well-understood drawback of the bi-level CES Armington formulation which may be circumvented by recalibrating the technical coefficients of the lower CES nest (e.g., using gravity-type schemes: Kuiper and van Tongeren, 2006; van Tongeren et al, 2007; Powers, 2007; Philippidis et al, 2012), a feature which is lacking in *Phoenix*. Even so, an open question is how applicable such innovations may be to trade in coal versus goods which are likely to be more widely produced (e.g., agricultural commodities). Bilateral coal trade depends on the fuel mix of the importing country, the rank and heat content of coal being traded, rail and water freight transport costs (which make up a substantial fraction of coal's import price) and non-economic considerations such as geopolitics. Although these factors may well shift in the future, neither the ways in which they might do so nor the implications for trade patterns is straightforward to predict. The critical imponderables are the extent to which coal importers will diversify their sources of supply to regions that they currently do not trade with—and what the consequences might be for global coal demand, GHG emissions and abatement costs. Space constraints mandate that we defer investigation of this issue to future research.

2.3 The Demand Side: Economic Expansion and Structural Change

Demand for coal is concentrated in a small number of sectors: electric power and refined petroleum and coal products, and to a lesser extent in mineral products and primary metals. The growth of developing economies is accompanied by a shift in the mix of output away from these sorts of energy and energy-intensive manufacturing industries, and toward low-energy and emission intensity service sectors, leading to future declines in the coal intensity of GDP. Models typically do not simulate the economic processes that underlie structural change, but rather parameterize declining dependence on energy through the use of an autonomous energy efficiency improvement (AEEI) parameter that reduces the coefficient on energy in sectors' cost functions and households' expenditure functions (see, e.g., Sue Wing and Eckaus, 2007), and customarily treat the consequent decoupling of energy use from economic growth as independent of climate policy. *Phoenix*'s baseline assumptions specify constant regionally-differentiated rates of growth of

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[4] The GTAP dataset gives the benchmark value of coal's upper-level domestic-import Armington elasticity of substitution as 3.05 and the lower-level inter-region elasticity as 6.1. Elasticity values for *Phoenix*'s other commodity aggregates range from 0.9 (Mining & Quarrying) to 5.2 (Refined Oil and Natural Gas) at the upper level, and from 2.5 (Fishing) to 8.45 (Non-Durable Goods) at the lower level. These parameters are the same for all regions. Ideally they should vary, but insufficient data often hinders empirical identification of interregional differences (see, e.g., van der Werf, 2008).

labor productivity and AEEI over three periods, 2005-35, 2035-75 and 2075-2100. The 2005-35 regional growth rates are calibrated to approximately match the rates of increase of real GDP and CO_2 emissions projected by EIA's International Energy Outlook. In later epochs they are tuned to produce plausible regional baseline projections of output and emissions that are roughly consistent with the SRES A2 high emissions scenario at the global level.

2.4 Climate Stabilization Policies and Carbon-Capture Technology

Stabilizing atmospheric GHG concentrations requires progressive abatement of emissions by all regions (Jacoby et al, 1997), which can cost-effectively be achieved through a system of harmonized national emission taxes that increase continually over time (e.g., Nordhaus, 2007, 2011). GHG taxes drive a wedge between the producer and consumer prices of coal in proportion to its emission content, driving up the consumer price which reduces the demand for coal by industry and conventional electric generation. (Oil and natural gas face similar but less intense economic pressures due to their lower embodied emissions.) Over time, the decline in the coal sector in the face of reduced demand for its output translates into a slower pace of resource depletion, associated productivity loss and cost increase.

The stringency of mitigation policies drives the market penetration of high-cost low- or zero-emission "backstop" energy supply technologies which cannot operate economically at the relative prices that prevail in a BAU scenario, and become active only when restrictions on the use of fossil fuels push their relative prices sufficiently high. The key technology we consider here is central-station electric power generation with CCS. As discussed above, emission constraints lower coal's pre-GHG tax price relative to other fossil fuels, making it attractive as an input to IGCC-CCS. This phenomenon is captured explicitly by *Phoenix*'s detailed representation of electricity production. The electric power sector is divided into eleven discrete generation options, of which the conventional coal and IGCC-CCS technologies produce electricity according to a CES cost function denominated over labor, capital and a mix of domestic and imported coal. The major competing generation option is NGCC-CCS, whose structural specification is similar but has natural gas as the fuel input and different technical coefficients. The central feature of both CCS technologies is that the emissions embodied in their fossil fuel inputs are sequestered and do not count against mitigation obligations. Associated with fuel use is a complementary demand for a sequestration "fixed-factor" resource, which represents the services of both pipeline CO_2 transport and geologic reservoir storage. IGCC-CCS and NGCC-CCS compete for sequestration capacity, which in each region is determined by an upward-sloping supply curve whose price elasticity is tuned to yield plausible patterns of market penetration.[5] IGCC-CCS and NGCC-CCS are backstop technologies that are assumed to become available in all regions in 2020 at a 30% penalty over the benchmark cost of their conventional counterparts, which guarantees that they are never operated in

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[5] The supply elasticity is 2 in all regions except China/Taiwan, where it is set to unity to reflect the technical and economic challenges of transporting and storing the vast quantities of CO_2 emitted by China/Taiwan's large coal generation base, and Japan and Korea where it is zero, reflecting these regions' small coal generation base and scarcity of geologic storage capacity.

	Baseline Parameter Assumptions	Economic Growth[a]		Structural Change[b]		Trade Diversification[c]		Depletion Penalty[d]
		High	Low	High	Low	High	Low	Low
BAU	(1)/[G1][e]	(2)	(3)	(4)/[G2][e]	(5)	(6)	(7)	(8)
Stabilize GHG concentrations at 550 ppm								
CCS	(9)/[G17][e]	(10)	(11)	(12)/[G18][e]	(13)	(14)	(15)	(16)
No CCS	(17)/[G19][e]	(18)	(19)	(20)	(21)	(22)	(23)	(24)
Stabilize GHG concentrations at 450 ppm								
CCS	(25)/[G9][e]							
No CCS	(26)/[G11][e]							

[a] +10% (High) and -10% (Low) changes in regional labor productivity growth rates
[b] × 1.85 (High) and ÷ 1.85 (Low) changes in regional AEEI growth rates
[c] × 2 (High) and ÷ 2 (Low) changes in lower-tier Armington elasticity for coal
[d] No reduction in the coal sector's productivity beyond the standard diminishing returns formulation
[e] Corresponding EMF 27 scenarios in square braces

Table 1 Numerical Experiments

the BAU scenario, but switch on and grow endogenously as electricity prices rise relative to the price of coal under climate policy. IGCC-CCS market penetration depends on several factors including electricity's price elasticity of demand, the increase in the marginal cost of conventional coal generation as a consequence of mitigation policy, mitigation's impact on the relative cost of competing natural gas generation (either conventional or NGCC), and coal's pre-GHG tax price.

3 Numerical Simulations

To assess the relative importance of these factors in *Phoenix* we expand upon the matrix of EMF 27 scenarios to run a total of 26 numerical experiments (Table 1). We perform simulations under our baseline parameter assumptions for a BAU scenario and a climate stabilization scenario which is equivalent to limiting atmospheric GHG concentrations below 550 ppm. The stabilization case assumes the imposition of a global GHG tax starting at \$15/ton CO_2 equivalent in 2020 and rising at an average annual rate of 5.7% to \$80/ton by 2050. We simulate two variants of this case, a "full technology" scenario in which NGCC-CCS and IGCC-CCS are assumed to become available in 2020, and a restricted scenario in which CCS technologies never become available. These three scenarios constitute our central cases which we then perturb to investigate the sensitivity of the global coal market's behavior to deviations across five dimensions. The first is the pace of economic growth, where we perturb baseline regional labor productivity growth rates by ± 10%. The second is structural change away from energy, where we increase baseline AEEI growth rates by 80% in developed regions and 90% in developing regions, and decrease them by 45% in developed regions and 48% in developing regions.[6] The third is trade diversification, where we double and halve the baseline value of the lower-tier Armington elasticity of substitution among each region's trade partners in the international coal market.[7] The fourth

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[6] Scenarios G2 and G18 lower all regions' energy intensities to 20% of their baseline levels.

[7] In the high elasticity case, regions' coal imports are essentially perfectly substitutable among trade partners, subject to the caveat of zero benchmark shares in the bilateral trade matrices.

is the accelerated decline in coal mining productivity due to depletion, which we remove by switching off the depletion penalty described in section 2.1. The final dimension is increased policy stringency, which we assess under baseline parameter assumptions by raising the GHG tax to start at \$32.50/ton in 2020, increasing at an annual average rate of 5.2% to \$150.50/ton by 2050.

Our experimental design reflects constraints established by the matrix of EMF 27 scenarios. As a case in point, scenario G20 specifies a tax to stabilize atmospheric GHGs below 550 ppm with CCS technology but without nuclear power. Pre-2050, projected coal production and use in this scenario differ only slightly from the full technology case. Accordingly, we forgo consideration of the former to conserve space. More consequential to our analysis is the large increase in the AEEI growth rate under scenarios G2 and G18, which substantially exceeds the plausible amplitude of variation in other input parameters. For this reason the magnitude of changes in model outputs must be normalized with respect to the parameter perturbations, which we do via a modified version of the procedure in Nordhaus (1994). Given a simulation horizon of $t = \{1, \ldots, T\}$ time periods, Nordhaus evaluates the sensitivity of the i^{th} model output variable ($x_{i,t}$) to the j^{th} input parameter (θ_j) by first perturbing the model with "test high" input values ($\boldsymbol{\theta}^H$),[8] and then computing the Euclidean distance of the target output variable from its level under baseline parameter assumptions ($\boldsymbol{\theta}^B$):

$$\mathcal{S}_{i,j}^{\text{Nordhaus}} = \sum_t \left\{ \left(x_{i,t}(\theta_j^H)/x_{i,t}(\theta_j^B) - 1 \right)^2 \right\}^{0.5}.$$

We extend this approach by using the change in the value of the target output variable in response to not just high but also low input values ($\boldsymbol{\theta}^L$), which we then normalize by the percentage change in the input perturbation relative to its baseline. The result is the average arc-elasticity:

$$\mathcal{S}_{i,j} = \frac{1}{T} \sum_{t=1}^{T} \left\{ (x_{i,t}(\theta_j^H) - x_{i,t}(\theta_j^L))/x_{i,t}(\theta_j^B) \right\} / \left[(\theta_j^H - \theta_j^L)/\theta_j^B \right]. \tag{1}$$

Our criteria variables i are world production and exports. Regarding the parameters j, when perturbing economic growth, structural change and trade diversification, the denominator in square brackets in eq. (1) is simply the percentages change in the growth rates of labor productivity, AEEI, and the Armington elasticity in Table 1. For the stabilization cases we use the percentage change in year-2050 GHG concentrations relative to the BAU under baseline assumptions. Because the resource depletion penalty elasticity is one-sided (only baseline and high productivity), we set $\theta_j^B = \theta_j^L$ and calculate the denominator as the production-weighted average change in regions' coal productivity.

4 Results

For expositional clarity we divide our discussion into two, dealing first with results at the global level (Figure 1) before moving on to highlight major drivers at the regional level (Tables 2 and 3, and Figure 2).

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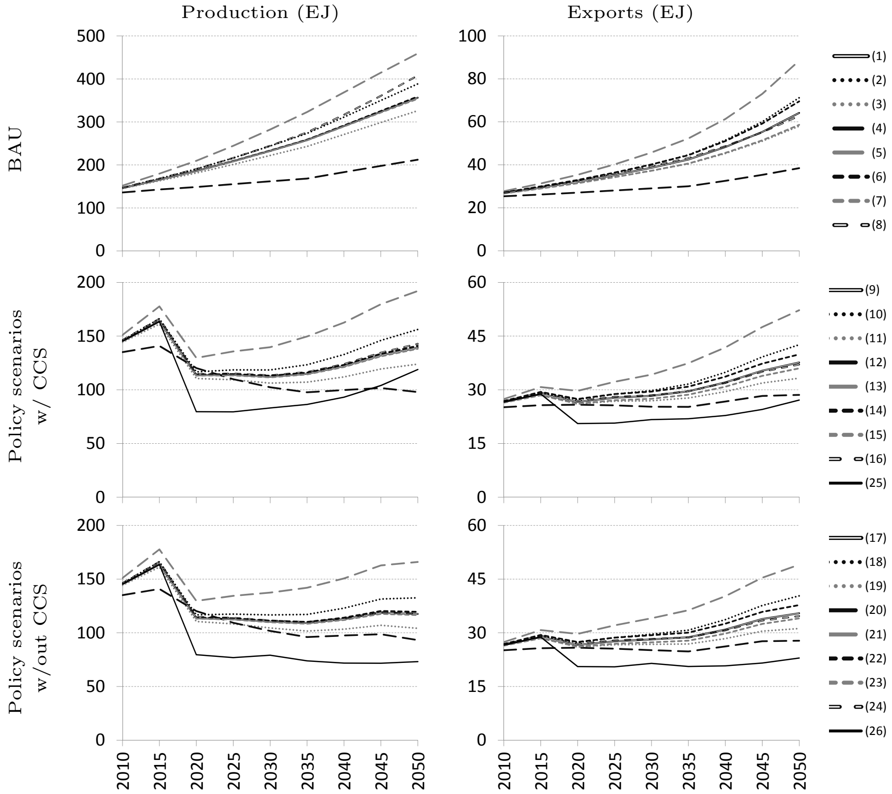
[8] In principle, this represents the 90th percentile of the range of values of the relevant parameter in the literature. In practice, the choice of value also involves a mix of judgment and assumptions.

A. World Coal Production and Export Trajectories (scenarios listed in Table 1)



B. Elasticities of World Coal Production and Exports to Perturbations (see eq. (1))

	GHG Conc. Reduction	Economic Growth	Structural Change	Trade Diversification	Depletion Penalty
	Production, 2010-2050				
BAU	–	0.11	-0.08	0.001	0.07
Stabilize GHG concentrations at 550 ppm					
w/ CCS	-0.81	0.13	-0.06	0.002	0.03
w/out CCS	-0.85	0.13	-0.06	0.002	0.02
Stabilize GHG concentrations at 450 ppm					
w/ CCS	-0.73				
w/out CCS	-0.81				
	Exports, 2010-2050				
BAU	–	0.10	-0.07	0.01	0.009
Stabilize GHG concentrations at 550 ppm					
w/ CCS	-0.45	0.13	-0.06	0.01	0.004
w/out CCS	-0.48	0.13	-0.06	0.01	0.000
Stabilize GHG concentrations at 450 ppm					
w/ CCS	-0.55				
w/out CCS	-0.59				

Fig. 1 World Coal Production and Exports, 2010-2050

Experiment	(1)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(17)	(25)	(26)
	2010	Cumulative 2010-2050											
		Baseline Assumptions	Economic Growth		Structural Change		Trade Diversification		Depletion Penalty	550 ppm Stabilization		450 ppm Stabilization	
			High	Low	High	Low	High	Low	Low	CCS	No CCS	CCS	No CCS
	Production: EJ (experiment 1) and % change from BAU scenario (other experiments)												
World	127.9	9413	5.1	-4.9	-29.0	20.4	0.4	-0.3	6.3	-55.0	-57.8	-54.4	-75.2
China/Taiwan	48.8	3910	6.3	-6.1	-32.5	21.4	-1.5	0.8	11.7	-46.2	-49.2	-47.7	-53.2
India	9.3	736	6.1	-6.0	-33.4	20.4	-1.1	0.7	11.1	-80.6	-86.2	-70.0	-77.7
USA	26.4	1201	3.9	-3.7	-30.8	25.8	3.3	-1.9	-2.1	-45.7	-47.7	-43.9	-46.6
	Resource depletion: % of resource base extracted												
World	0.2	3.6	3.8	3.4	2.6	4.3	3.6	3.6	3.8	2.1	2.1	1.8	1.7
China/Taiwan	1.4	26.0	27.4	24.7	18.8	30.8	25.7	26.2	28.5	15.2	14.8	12.8	11.7
India	1.2	22.1	23.3	21.0	15.7	26.1	21.9	22.2	24.1	7.2	6.6	6.8	5.5
USA	0.2	2.3	2.3	2.2	1.7	2.7	2.3	2.2	2.2	1.5	1.4	1.2	1.1
	Exports: EJ (experiment 1) and % change from BAU scenario (other experiments)												
World	24.2	1605	4.7	-4.3	-24.8	19.8	4.4	-4.1	1.0	-32.3	-34.1	-39.9	-59.5
Australia/N. Zealand	6.6	398	3.8	-3.5	-28.8	21.5	-5.3	-0.4	-16.6	-12.6	-14.0	-20.4	-22.3
China/Taiwan	3.3	186	3.4	-3.6	-9.1	3.5	-19.6	2.0	26.7	9.0	9.7	-16.2	-15.8
Russia	2.2	193	9.0	-8.2	-33.7	25.0	39.6	-24.7	-22.7	-44.2	-46.4	-54.8	-56.8
	Imports: EJ (experiment 1) and % change from BAU scenario (other experiments)												
China/Taiwan	2.3	183.3	8.6	-7.7	-44.9	39.9	13.4	-13.6	0.7	29.1	29.6	-7.3	-8.5
India	0.8	85.1	10.9	-9.8	-41.9	29.9	4.0	-2.8	-6.5	112.2	116.0	39.1	43.0
USA	0.7	20.6	1.2	-1.2	-15.8	9.0	5.2	-3.5	23.2	-24.5	-24.4	-50.2	-50.5
	Sectoral coal use: EJ (experiment 1) and % change from BAU scenario (other experiments)												
World													
Industry[a]	33.2	2144	4.3	-4.2	-20.9	11.5	0.2	-0.1	6.7	-43.5	-43.5	-55.3	-54.6
Conventional elec.	81.0	5842	5.3	-5.1	-33.3	24.9	0.1	0.0	6.6	-49.4	-48.3	-62.9	-61.2
IGCC-CCS elec.[b]	–	–	–	–	–	–	–	–	–	4.0	–	8.6	–
	Coal emissions: GT (experiment 1) and % change from BAU scenario (other experiments)												
World	13.4	869	5.2	-4.9	-29.1	20.3	0.1	0.0	6.9	-48.5	-47.8	-60.8	-59.8
China/Taiwan	5.3	404	6.0	-5.7	-31.5	21.1	0.1	0.1	9.4	-46.6	-45.6	-59.6	-57.7
India	1.4	106	6.0	-5.8	-31.9	19.8	-0.4	0.3	8.6	-61.5	-61.0	-69.2	-68.5
USA	2.3	111	2.7	-2.6	-26.6	21.0	-0.2	0.1	0.9	-40.5	-40.1	-54.8	-54.3
	Total emissions: GT (experiment 1) and % change from BAU scenario (other experiments)												
World	30.0	1724	3.9	-3.7	-22.6	14.5	0.0	0.0	3.5	-32.8	-32.4	-44.0	-43.4
China/Taiwan	6.8	506	5.8	-5.5	-30.3	20.2	0.1	0.0	7.8	-41.2	-40.4	-53.4	-51.8
India	1.9	142	5.7	-5.5	-29.6	17.7	-0.3	0.2	6.5	-49.4	-49.0	-57.7	-57.1
USA	6.0	272	1.9	-1.8	-19.7	14.2	-0.1	0.0	0.4	-23.9	-23.7	-34.7	-34.4

[a] Petroleum/coal products, Chemicals/rubber/plastics, Non-metallic materials, Iron/steel, Non-ferrous metals. [b] % of baseline conventional electricity generation.

Table 2 World coal markets: 2010 and cumulative 2010-2050.

Experiment	(9)	(17)	(10)	(18)	(11)	(19)	(12)	(20)	(13)	(21)	(14)	(22)	(15)	(23)	(16)	(24)	(25)	(26)
	Cumulative 2010-2050																	
	Baseline Assumptions		Economic Growth				Structural Change				Trade Diversification				Depletion Penalty		450 ppm Stabilization	
			High		Low		High		Low		High		Low		Low			
	Coal Production: % change from experiment 1																	
World	-55	*-58*	-42	*-44*	-47	*-65*	-51	*-66*	-33	*-53*	-44	*-62*	-45	*-63*	-44	*-62*	-54	*-75*
China/Taiwan	-19	*-21*	-7	*-8*	-13	*-14*	-23	*-24*	6	*5*	-15	*-16*	-9	*-10*	-20	*-21*	-25	*-27*
India	-81	*-86*	-66	*-70*	-70	*-73*	-70	*-71*	-62	*-66*	-67	*-70*	-69	*-72*	-68	*-72*	-70	*-78*
USA	-46	*-49*	-33	*-35*	-41	*-43*	-46	*-47*	-23	*-25*	-37	*-39*	-37	*-39*	-35	*-38*	-48	*-53*
	Coal Resource Base Depletion: % of resource base extracted																	
World	2.1	*2.1*	2.2	*2.2*	2.0	*2.0*	1.9	*1.9*	2.5	*2.4*	2.1	*2.1*	2.1	*2.1*	2.2	*2.1*	1.8	*1.7*
China/Taiwan	15.2	*14.8*	16.1	*15.7*	14.4	*14.1*	13.2	*13.2*	18.2	*17.8*	15.1	*14.8*	15.2	*14.8*	15.5	*15.1*	12.8	*11.7*
India	7.2	*6.6*	7.5	*6.9*	6.9	*6.4*	6.9	*6.8*	8.4	*7.6*	7.4	*6.8*	7.1	*6.5*	7.1	*6.5*	6.8	*5.5*
USA	1.5	*1.4*	1.5	*1.5*	1.4	*1.4*	1.4	*1.4*	1.7	*1.7*	1.5	*1.5*	1.5	*1.4*	1.4	*1.4*	1.2	*1.1*
	Coal Exports: % change from experiment 1																	
World	-32	*-34*	-20	*-22*	-28	*-47*	-33	*-50*	-9	*-29*	-22	*-40*	-26	*-45*	-24	*-43*	-40	*-59*
Australia/N. Zealand	-13	*-14*	-2	*-3*	-9	*-9*	-21	*-21*	12	*11*	-12	*-13*	-4	*-4*	-18	*-19*	-20	*-22*
China/Taiwan	9	*10*	24	*25*	6	*6*	6	*6*	33	*34*	9	*10*	9	*9*	21	*20*	-16	*-16*
Russia	-44	*-46*	-33	*-34*	-42	*-44*	-42	*-43*	-24	*-26*	-18	*-21*	-48	*-50*	-50	*-51*	-55	*-57*
	Coal Imports: % change from experiment 1																	
China/Taiwan	29	*30*	19	*19*	2	*2*	-33	*-32*	45	*46*	14	*15*	5	*6*	17	*17*	-7	*-8*
India	112	*116*	89	*92*	60	*62*	15	*15*	116	*119*	75	*78*	73	*75*	78	*80*	39	*43*
USA	-24	*-24*	-30	*-30*	-34	*-34*	-32	*-32*	-21	*-21*	-31	*-31*	-32	*-32*	-27	*-27*	-50	*-51*
	Sectoral Coal Use: % change from experiment 1																	
World																		
Industry^a	-44	*-43*	-41	*-41*	-46	*-46*	-45	*-45*	-36	*-36*	-43	*-43*	-44	*-44*	-43	*-43*	-55	*-55*
Conventional elec.	-49	*-48*	-47	*-46*	-52	*-51*	-55	*-54*	-37	*-36*	-49	*-48*	-49	*-48*	-49	*-48*	-63	*-61*
IGCC-CCS elec.^{b}	4.0	-	4.4	-	3.7	-	1.0	-	5.3	-	4.0	-	4.1	-	4.5	-	8.6	-
	Coal Emissions % change from experiment 1																	
World	-48	*-48*	-46	*-45*	-51	*-50*	-53	*-52*	-38	*-37*	-48	*-48*	-49	*-48*	-48	*-47*	-61	*-60*
China/Taiwan	-47	*-46*	-43	*-42*	-50	*-49*	-54	*-54*	-34	*-33*	-47	*-46*	-47	*-46*	-46	*-45*	-60	*-58*
India	-61	*-61*	-59	*-59*	-64	*-63*	-66	*-66*	-54	*-53*	-61	*-61*	-61	*-61*	-61	*-61*	-69	*-69*
USA	-40	*-40*	-39	*-38*	-42	*-42*	-44	*-44*	-28	*-27*	-40	*-40*	-40	*-40*	-40	*-40*	-55	*-54*
	Total Emissions % change from experiment 1																	
World	-33	*-32*	-30	*-30*	-35	*-35*	-24	*-23*	-38	*-38*	-33	*-32*	-33	*-32*	-32	*-32*	-44	*-43*
China/Taiwan	-41	*-40*	-38	*-37*	-45	*-44*	-51	*-50*	-28	*-27*	-41	*-40*	-41	*-40*	-41	*-40*	-53	*-52*
India	-49	*-49*	-47	*-46*	-52	*-52*	-56	*-56*	-41	*-41*	-49	*-49*	-49	*-49*	-49	*-49*	-58	*-57*
USA	-24	*-24*	-22	*-22*	-25	*-25*	-31	*-31*	-13	*-13*	-24	*-24*	-24	*-24*	-24	*-24*	-35	*-34*

[a] Petroleum/coal products, Chemicals/rubber/plastics, Non-metallic materials, Iron/steel, Non-ferrous metals. [b] % of baseline conventional electricity generation.

Table 3 World coal markets under GHG stabilization: cumulative 2010-2050 (roman figures indicate scenarios with CCS technology, italics indicate scenarios without).

4.1 Global Trends

4.1.1 The BAU scenario

The trajectories of global production and exports of coal are shown in panel A of Figure 1. Our first key result is that under baseline assumptions, by 2050 global coal production and exports are both projected to nearly triple, from 128 EJ in 2010 to 356 EJ, and from 24 EJ to 64 EJ, respectively. The global primary energy supply becomes more coal-intensive as well, with its share of the energy mix rising by nearly one third, from 30% in 2010 to 39% in 2050. A direct consequence is that coal's share of global CO_2 rises by 25% to exceed half of world emissions by 2050, generating a cumulative atmospheric release of 1000 GT of CO_2 over these four decades. By way of context, McFarland et al's projections are more bullish, exceeding our 2050 global production and use by 26%.

Looking first at influences on the trajectory of production, the effect of trade diversification is very slight, while that of economic growth is larger, around ± 10 %. Our changes in AEEI have by far the largest influence, raising the trajectory by 30% and and lowering it by 40%. Lowering the productivity loss from resource depletion increases production by 14%. Turning to world exports, economic growth and trade diversification have similar influences, with our scenarios generating similar shifts in the baseline trajectory of around ± 10%. Structural change has a substantial influence, shifting the baseline by around ±40 %, while reducing depletion's cost has a negligible impact.

This leads to our second key finding, namely, the importance of assumptions about economic growth, and, to a lesser extent, AEEI in projecting the character of the world coal market in the absence of climate policy shown in Figure 1 panel B. The sensitivity of production and exports to all parameters is low ($|\mathcal{S}| < 0.15$). Coal production varies most with assumptions about economic growth, but its responses to changing assumptions about resource depletion costs and energy efficiency-driven structural change are an order of magnitude smaller, and it is insensitive to trade diversification. The pattern is somewhat similar for exports, except they are an order of magnitude more responsive to the subtitutability of import partners, and insensitive to the depletion penalty.

4.1.2 GHG stabilization scenarios

Stabilizing atmospheric GHG concentrations substantially reduces coal emissions, and in turn its use, extraction and trade. Relative to the BAU scenario, 2010-50 cumulative CO_2 emissions fall by 33% and 44% under the 550 ppm and 450 ppm policies, with corresponding declines in the cumulative CO_2 from coal combustion of 48% and 61%. By 2050 coal is responsible for only one third of world emissions in the 550 ppm scenario and 27% in the 450 ppm scenario. Corresponding figures in the no-CCS cases are slightly larger, reflecting the inability to sequester the CO_2 from coal combustion. Coal's share of global primary energy supply shrinks to 23% (20% if CCS is unavailable) in the 550 ppm scenario and 21% (14% if CCS is unavailable) in the 450 ppm scenario. The initial onset of the CO_2 tax is associated with an immediate large drop in coal use and production (39% and 57% from the baseline value in the 550 ppm and 450 ppm scenarios, respectively), a result which reflects the abundant substitution possibilities assumed in *Phoenix*'s baseline parameterization.[9]

Our third key finding is that this precipitous decline is unlikely to persist, but is followed by a stabilization and slight increase in coal production, the latter being more pronounced when CCS technology is available. In that case, by 2050 production recovers from its 2020 nadir to 131 EJ in the 550 ppm scenario and 113 EJ in the 450 scenario, with lower corresponding figures without CCS availability (109 EJ and 68 EJ), culminating in an overall reduction in supply from BAU levels of 61%-79%. While our GHG taxes are substantially higher than McFarland et al, our findings are qualitatively similar: along the 550 ppm tax path world coal production returns to near today's levels by 2050 under a variety of structural assumptions—but only if CCS is available. If it is not, the global coal industry is 20%-25% smaller than today, approximately the same size as in the 450 ppm tax scenario with CCS available. In this more stringent case, without CCS the coal market shrinks to half its current size.

On the demand side, the onset of the tax in the 550 ppm scenario induces an immediate 40% drop in coal use by conventional electric power generation, followed by a more gradual decline to 73% below the BAU level in 2050. In the 450 ppm scenario this pattern is more pronounced, exhibiting reductions of 53% initially and 87% in the long run. Without CCS the trajectory is the same in each case, but with the ultimate decline being smaller by 2-3 percentage points. Both policy scenarios see industrial coal use respond in the same manner, but with smaller reductions in the short and the long run (36% and 63%, respectively). In the runs where IGCC-CCS in available it comes on line in 2025 using less than 2 EJ of coal but expands rapidly, by 2050 accounting for 27 EJ and 54 EJ of coal in the 550 and 450 ppm cases, equivalent to 21% and 48% of global coal demand. In both absolute and percentage terms, rapid AEEI growth has the biggest impact on IGCC-CCS coal use, which is 75% smaller than under baseline parameter assumptions.

Over the course of the simulation, the price pressure of the rising GHG tax is outstripped by the countervailing expansionary effect of world economic growth on the demand for coal, with the result that coal abatement is more elastic in the early years when tax levels are comparatively low. Even so, in Figure 1 panel B the overall elasticity of coal production with respect to the reduction in atmospheric GHGs is the largest of all the factors we consider, especially when the compensating influence of IGCC-CCS technology is absent. Production's sensitivity to the other driving forces is similar to the BAU scenario except for the depletion penalty, whose impact is half as large. The reason is that the associated extraction cost savings are marginal compared to those achieved by the reduction in depletion in response to the 55%-72% tax-induced decline in coal demand over the period 2020-50. Additionally, production's baseline response is less elastic in the 450 ppm stabilization case, with the incremental tightening of 2050 GHG concentrations exceeding the incremental reduction in coal demand. In this more emission-constrained setting, oil and gas shoulder a larger share of the abatement

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[9] An additional key factor is the assumption of capital malleability. Models such as MIT-EPPA (Paltsev et al, 2005) that embody a vintage capital specification typically exhibit larger price changes and a smoother path of quantity adjustment over the short-run transition to the policy shock. This is a consequence of the smaller aggregate elasticity of substitution on the supply side.

burden at high tax levels, which suggests that coal's long-run abatement elasticity is declining in the tax.

Our fourth key result is that, compared to production, global coal export trajectories are much less responsive to GHG taxes. In both stabilization cases world coal trade declines only slightly in 2020 before returning to slower growth (0.9% and 0.7% per annum with and without CCS, respectively) relative to the BAU scenario (2.2% per annum), culminating in a reduction in trade of 41%-64% from BAU levels by 2050. This behavior reflects the Armington formulation's tendency to preserve both the levels and interregional patterns of trade. As with production, the impact on trade of reductions in 2050 GHG concentrations is significantly more elastic than the other driving forces—whose elasticities are largely the same those in the BAU scenario. Interestingly, however, while trade's sensitivity to GHG abatement is lower than that of production (consistent with our findings above), additional reductions in coal use and import demand from higher GHG taxes in the 450 ppm scenario stimulate *increased* responsiveness. As we shall see, this behavior stems from the fact that major coal importing regions generally import less under more stringent emission constraints.

4.2 Regional Highlights

4.2.1 The BAU scenario

The aforementioned global responses are underlain by the dynamics of demand, production and trade at the regional level. We focus attention on the behavior of regions that are the largest cumulative producers and consumers (China/Taiwan, USA, and India) and exporters (Australia/New Zealand, Russia, and China/Taiwan) over the 2010-2050 time-frame. In 2010, the three largest producing regions account for 68% of global coal supply: China/Taiwan, the USA and India, with 60, 28 and 11 EJ respectively. In 2050 there is no change in the ranking of the top five producers under any of our BAU projections. China/Taiwan remain the largest user of coal with demand expanding by a factor of 3.6 from 2010. India's coal use quadruples, surpassing that of the US which increases by 65%. Production in China/Taiwan and India expands faster than in the US (average annual rates of 2.6% and 3% versus 1.4%), with China/Taiwan's share of global supply increasing alongside its domestic demand, from 41% in 2010 to 50%. Over this period, China, USA and India respectively account for 49%, 14% and 10% of global coal use and 46%, 13% and 12% of global coal emissions. However, minor players in the world market such as Central & Other Asia, Brazil and Sub-Saharan Africa see the fastest growth in coal use and emissions. Regarding trade, Australia/New Zealand, Russia and China/Taiwan account for 51% of world exports in 2010, and go on to expand their collective share to 56% in 2050 while exhibiting heterogeneous patterns of growth (average annual rates of 2.3%, 3.8% and 1.2%, respectively). By contrast, the US, which is the fifth largest exporter with 7% of the global market in 2010, grows at 4% per annum, which puts it on track to surpass Australia/New Zealand by the second half of the century.

Our fifth major finding is that interregional differences in rates of depletion are the fundamental driver of shifting regional shares of world coal production.[10] Under baseline assumptions, by 2050 both Russia and the US extract less than 2% of their respective coal resource bases, whose large size translates into low marginal costs of extraction. Faster depletion of the coal resource base in China/Taiwan, India and, to a lesser degree, Australia/New Zealand (which extract 26%, 22%, and 5% of their resource, respectively) results in steeper declines in productivity and increases in extraction costs, and lead to China/Taiwan's supply price being among the highest in 2050. India's coal price in the benchmark year is the lowest of any region in the model's benchmark year, and remains among the lowest in 2050 despite the growth in domestic demand and the regional diversification of its exports. The upshot is a shift in comparative advantage away from relatively high-cost coal from Australia/New Zealand and China/Taiwan, and toward relatively low cost coal from Russia and the USA.

Despite this, the CES-Armington specification's share-preserving character means that importers are slow to shift away from Australia/New Zealand, China/Taiwan and other high-cost suppliers as their prices rise relative to those of their cheaper competitors. Over the period 2010-50, China/Taiwan's share of world exports falls from 14% to 10%,[11] while Russia and USA's shares increase from 9% to 15% and 7% to 11%, respectively. This result reflects a balance of forces: expansion of global coal demand tends to increase the demand for Australia/New Zealand and China/Taiwan's exports relative to Russia, USA and India's, while depletion-driven changes in relative prices push in the opposite direction.[12]

Trade diversification aside, the sensitivity of top producers' coal supplies to parameter perturbations mirrors the responses at the global level. Positive labor productivity perturbations induce cumulative production increases of 6% in China/Taiwan and India and 4% in USA, with symmetric opposite responses to negative perturbations. Raising the AEEI induces similar percentage declines in cumulative production in the USA, China/Taiwan and India (between -32% and -34%, similar in magnitude to the world average). Lowering the AEEI induces more heterogeneous increases (21%, 22% and 27% in India, China/Taiwan and USA, respectively). On a normalized basis, however, regional production responds less elastically to assumptions about structural change than to economic growth. Perturbing the Armington elasticity and resource productivity elicits the most diverse production responses among the top regions. Increasing trade-partner subtitutability triggers a 3% rise in the US and declines of 1% and 2% in India and China/Taiwan, while lowering subtitutability reduces USA's production by 2%, and increases both China/Taiwan's and India's by 1%. Removing the depletion penalty increases cumulative production in India and China/Taiwan by 11% and 12% while lowering it by 2% in the U.S. Lastly, the sign and magnitude of the corresponding changes in cumulative demand by the largest consuming regions closely follows their shifts in production, with the exception of perturbations to trade and resource productivity. In the former case there is no noticeable change

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[10] This result is not apparent from our perturbation experiments because these involve changing depletion costs for *all* regions simultaneously.

[11] The majority of trade is between the countries in this region.

[12] Indeed, India's tiny share of world exports in the GTAP dataset is the reason its market share never exceeds 1% despite its low supply price.

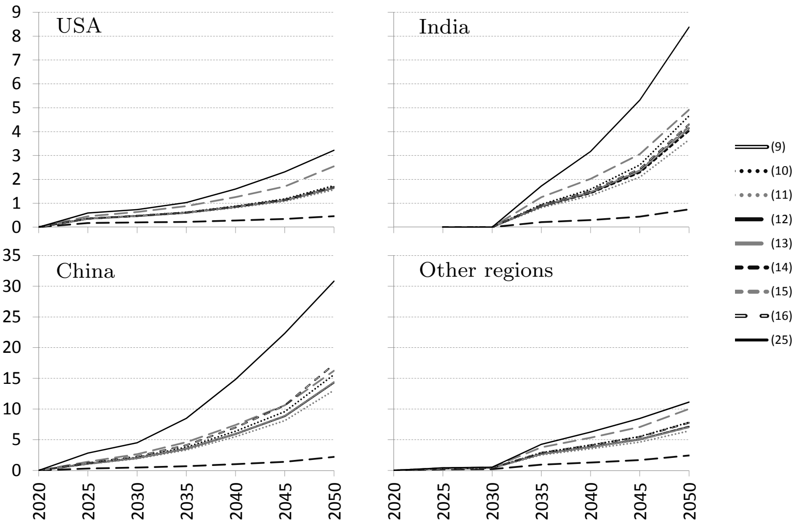

Fig. 2 Coal Use by IGCC-CCS (EJ, scenarios listed in Table 1)

in cumulative demand from the BAU scenario, while in the latter USA's decreases increases slightly.

Regions' export responses to perturbations differ from those at the global level. Changing labor productivity assumptions induces shifts in cumulative exports that are larger in Russia (+9% and -8% in the high and low economic growth scenarios), and smaller and equal in both China/Taiwan and India (± 4%). The structural change cases shift exports in Australia/New Zealand and Russia in line with the global average (-30% and 22% in the high and low cases for Australia/New Zealand, and -35% and 26% for Russia). China's exports are much less responsive to both scenarios, decreasing by 9% in the high structural change scenario and increase by a mere 4% in the low structural change case. Not unexpectedly, changing the subtitutability of trade partners induces heterogeneous and asymmetric export responses at the regional level. Doubling the Armington elasticity leads to a 40% increase in Russian exports, a 5% drop in Australia/New Zealand and a dramatic decline of 21% in China/Taiwan. When the elasticity is halved and trade patterns are less sensitive to relative prices, Australia/New Zealand's cumulative exports match their levels from the reference case, China/Taiwan's increase by 2%, and Russia's decrease by 25%. Exports from the top regions are more sensitive to reduced extraction costs than the 1% increase we measure at the global level: China/Taiwan increases by 28%, while Russia and Australia/New Zealand decline by 23% and 17%.

4.2.2 Stabilization policy scenarios

GHG taxes increase regions' consumer prices of coal, which depresses demand and extraction below BAU levels in all regions. The time-paths of regional consumption and production mirror the corresponding trajectories at the global level. In the 550 ppm scenario, 2020-50 cumulative coal use declines below BAU levels by the largest absolute amounts in top consuming regions (2336 EJ in China/Taiwan, 650 EJ in India and 615 EJ in the US), and by the largest percentage amounts in regions with smaller consumption (-73% in Canada and Central/Other Asia, -71% in Mexico). Higher taxes in 450 ppm scenarios amplify these declines while preserving the regional ordering of the largest absolute reductions. The coal industry's regional fortunes vary in conjunction with these shifts: in the 550 ppm scenario U.S. and India's production decline by 37% relative to 2010 levels, while China/Taiwan's *grows* by 21%. In the 450 ppm scenario the corresponding changes are -58%, -12% and +7%.

China/Taiwan's increase and India's rebound are fueled by the penetration of IGCC-CCS, which is a significantly larger contributor to electric power in these regions compared to the U.S. This is our sixth major finding. Under the 550 ppm scenario, conventional electricity's coal demand drops sharply in 2020, after which it stagnates in China/Taiwan, resumes growing at 1.7% per year in India, and continues to decline by 1.6% per year in the US and other regions. In this scenario the demand for coal by IGCC-CCS is less than 2 EJ, 4 EJ and 14 EJ in USA, India and China/Taiwan, respectively, constituting 11%, 28% and 20% of these regions' total demands. IGCC-CCS comes on line in 2025 in the U.S. and China/Taiwan but in India enters only in 2035 and grows rapidly, with coal demand suprassing the U.S. after a decade. Under the 450 ppm scenario conventional electricity's coal demand declines monotonically in all regions except India, where it continues to increase at 1.3% per year. By 2050 USA's, India's and China/Taiwan's IGCC-CCS coal use increases to 3 EJ, 8 EJ and 31 EJ, for 33%, 56% and 47% of total demand.

These results highlight the trade consequences of interactions between the penetration of IGCC-CCS and regions' relative rates of depletion. On the domestic side, increased demand for domestic coal at pre-tax prices by an expanding IGCC-CCS technology more rapidly deplete the domestic resource, increasing extraction costs and the gross-of-GHG tax domestic coal price. On the import side, because coal trade occurs at pre-GHG tax prices, regions whose import demands are satisfied by producers with large resource bases and low extraction costs enjoy low weighted-average Armington import prices, and in turn, lower gross-of-tax prices of imported coal. This phenomenon is evident in Australia/New Zealand, China/Taiwan and India in the 550 ppm scenarios, and in India in the 450ppm scenario, where imports progressively substitute for domestic coal, so much so that imports exceed their BAU levels on a cumulative basis.

In India, domestic production satisfies 93% of 2010 coal demand, a share which falls to 85% and 45% by 2050 in the BAU and 550 ppm scenarios. In the former scenario, the average annual rates of change in the prices of domestic and imported coal are 1.5% and 0.5%; in the latter, import penetration is larger as the gross-of-tax domestic price rises at 6.7% per annum compared to imported coal's 3.7%. As IGCC-CCS' pre-tax domestic coal price is uniformly lower than the import price, this activity is the only one in which domestic coal expands its market share. When CCS technology is not available, coal use is 25% lower in 2050, and domestic production supplies only 24% of demand. In the 450 ppm scenario, production and consumption of domestic coal both exceed the 550 ppm scenario as a consequence of heavier reliance on IGCC-CCS, without which 2050 coal production is less than one-fifth as large, causing domestic coal's consumption share to fall to 18%.

China/Taiwan's price of imported coal grows faster than the domestic price until 2025 in the BAU scenario, after which imports become increasingly competitive (price growing at an annual average rate of 1.3% versus domestic coal's 1.7%). Similar to India, domestic coal's gross-of-GHG tax price exceeds the import price, but its pre-tax price rises less quickly, inducing expansion of IGCC-CCS. In 2010, 95% of coal consumption is met by domestic supplies—a pattern which continues in the BAU scenario, but this share falls to 88% and 86% in the 550 ppm stabilization scenarios with and without CCS, and 89% and 84% in the corresponding 450 ppm scenarios. China/Taiwan's decline in cumulative coal production relative to the BAU is half as large as India's. Coal production is buoyed by demand for exports, which are 14% higher in the 550 ppm scenario, a consequence of larger benchmark Armington shares in importing regions, and lower extraction costs.

5 Summary

Coal is the most carbon-intensive energy source, and is therefore expected to shoulder the largest abatement burden under policies to stabilize atmospheric GHG concentrations. Using a multi-regional, multi-sectoral dynamic CGE model, we assess the future of the global coal market under alternative climate stabilization regimes, and assessed the sensitivity of its production, trade and use to different assumptions about the structure of the world economy and the availability of mitigation technology.

Several interesting results emerge from our analysis. First, in the absence of climate policy coal is expected to remain the dominant source of energy globally, with production and exports nearly tripling by 2050. The size of the coal market is most sensitive to our assumptions regarding economic growth and, to a lesser extent, energy intensity. Second, imposing increasing taxes on GHG emissions causes coal extraction to decline significantly at first and then rebound—but only if CCS technology is available by 2020, in which case with a 550 ppm stabilization scenario coal production returns to todays levels by 2050 under a range of structural assumptions. We also find that global coal exports are much less responsive to GHG taxes than production, due to the preservation of both the levels and interregional patterns of international coal movements by our model's CES-Armington trade formulation. Third, interregional differences in rates of depletion are the fundamental driver of shifting regional shares of world coal production over time. In a BAU scenario both the US and Russia extract smaller shares of their respective large resource bases than large coal exporters such as China/Taiwan and Australia/New Zealand, which over time allows the US and Russia to enjoy lower relative marginal extraction costs and comparative advantage in coal production. Simultaneously, however, the Armington formulation retards coal importers' ability to shift to relatively low-cost sources of supply. Finally, under alternative climate stabilization regimes, coal's future in major producing and consuming regions is highly dependent upon the penetration of IGCC-CCS technology. IGCC-CCS' absolute levels and percentage shares of electricity generation in India and USA are both substantially lower than in China/Taiwan, which coincides with declines in coal production in the former regions and increases in the latter.

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Appendix: The *Phoenix* Energy-Economy Model

Phoenix is a dynamic multi-regional, multi-sectoral CGE model developed by Boston University, the Pennsylvania State University, and the University of Maryland Joint Global Change Research Institute. The model simulates the global economy and energy use to the year 2100 in 5-year time-steps. The model divides the world into 24 regional economies, each of which is represented by 26 industry sectors on the supply side, a representative household on the demand side, and a government which collects taxes and disburses the proceeds as subsidies to firms and transfers to households (Table 4). (Full documentation of the model is available online at `http://www.globalchange.umd.edu/models/phoenix/`.) The representative agent owns the factors of production (labor, capital, land, energy resources of different types) which it rents to domestic firms in return for compensation. Firms combine intermediate commodity inputs and primary factor inputs to produce output according to nested constant elasticity of substitution (CES) technologies. Commodity outputs are purchased by firms and households, both domestically and in other regions. Factor remuneration and net government transfer payments determine the household's income, which finances saving and current consumption. The latter is determined by nested CES preferences over domestic and imported commodities. The elasticities of substiution in the nested cost and expenditure functions take on identical values across regions, with the result that differences in production and demand derive solely from differences in the CES share parameters, which are a function of its benchmark calibration database, and relative prices as *Phoenix* solves for the static general equilibrium of the world economy each 5-year time-step. Equilibrium is formulated as a square system of nonlinear equations (zero profit for producers, supply-demand balance for commodities and factors, and income-expenditure balance and savings-investment balance for every regional representative agent) numerically calibrated using Global Trade Analysis Project (GTAP) version 7 database (Badri and Walmsley, 2008), and is expressed as a mixed complementarity problem and using the MPSGE subsystem Rutherford (1999) for GAMS (Brooke et al, 1998) and solved using the PATH solver (Ferris and Munson, 2000). The model steps through time in a myopic fashion, with a constant marginal propensity to save out of households' current income determining

Table 4 Sectors, Regions and Technologies in *Phoenix*

Sectors	Regions	Discrete Technologies
Agriculture	Australia & New Zealand	*Electricity Supply*
Air transport	Brazil	Conventional coal
Chemicals, rubber & plastics	Central America & Caribbean	Natural gas
Clothing & apparel	Canada	Conventional oil
Construction	Central & Other Asia	Hydro[b]
Coal[a,b,c]	China & Taiwan	Nuclear[b]
Electricity[a]	Eastern Other Europe	Wind[b]
Fishing	European Union 15	Solar[b]
Forestry	Indonesia	Biomass electricity
Food & Tobacco	India	Geothermal[b]
Gas[a,b,c]	Japan	NGCC-CCS[b,d]
Iron & steel	Korea	IGCC-CCS[b,d]
Non-durable goods	Middle East	*Other Fuel Supply*
Non-ferrous metals	Mexico	Liquid biofuel
Non-metallic minerals	North Africa	Coal gasification[d]
Crude oil[a,b]	Other European Union 27	*Demand*
Machinery & equipment	Other Latin America	Conventional hhold own-supplied transport
Mining & quarrying	Russia	
Other transport	Rest of World	Electric hhold own-supplied transport[d]
Paper & publishing	South Asia	
Refined petroleum & coal[a,c]	Sub-Saharan Africa	Biofuel hhold own-supplied transport
Services	USA	
Transport equipment	Western Other Europe	Electric water transport[d]
Water transport	South Africa	Biofuel water transport[d]
Wood products		Electric other transport[d]
Rest of economy		Biofuel other transport[d]

[a] Energy supply sector
[b] Sector or technology with an associated regional fixed-factor resource base
[c] Commodity used in CO_2 accounting
[d] Backstop technology not available in benchmark year.

the level of new capital formation. Over time, accumulation of the capital stock, together with assumptions about region-specific rates of increase of population, aggregate labor productivity, energy intensity decline, and resource productivity, determine the simulated regions' BAU trajectories of economic output, prices and CO_2 emissions.

Particular attention is paid to energy technology detail. Energy quantities are measured in exajoules (EJ) with prices in US$2005/EJ. In addition to electricity generation, there are four intermediate energy commodities: crude oil, refined oil products, coal, and natural gas. Coal gasification and liquid biomass are introduced as backstop technologies for the gas and refined oil commodities respectively. GTAP's single electricity sector is separated into production by coal, gas, oil, biomass, nuclear, wind, solar, and hydro, using the calibration procedure described in Sue Wing Sue Wing (2006), Sue Wing (2008). Carbon capture and sequestration technology is a backstop technlogy assumed to be available in 2020 to generated electricity from coal (IGCC-CCS) and gas (NGCC-CCS), but with unit costs of production higher than their conventional alternatives.