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Phase-out of 'coal to power' in an ETS

Thomas Eichner, Rüdiger Pethig

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Abstract

We investigate the displacement effects of phase-out-of-coal policies in a stylized model of electricity generation and CO2 regulation, in which a group of countries operates an emissions trading scheme (ETS). Electricity markets are either international or national and the emissions cap remains either unchanged or is tightened. With constant emissions cap and trade in electricity, some emissions as well as some coal-based electricity 'leak' into other countries and the aggregate welfare of the group of countries declines, if a country unilaterally phases out coal. With constant emissions cap and no trade in electricity, the unilaterally phasing-out country is worse off and the other countries are better off. Following a suggestion in a recently revised EU ETS Directive, we then combine a country's phase-out policy with canceling the permits it formerly used to generate electricity from coal. When electricity is traded, that combined policy prevents the leakage of emissions and coal-based electricity and shifts a share of the welfare costs to other countries. Without trade in electricity, the other countries generate less coal-based electricity and all countries' consumption welfare decreases, but all countries benefit from reduced climate damage. Finally, we offer an empirical calibration of our model to the European Union.

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1 Introduction

To prevent carbon emissions from exceeding the carbon budget implied by the ambitious climate target of the Paris agreement, large deposits of fossil energy resources must remain untapped (McGlade and Ekins, 2015). Coal deposits, in particular, need to be left in the ground, because these are the most emissions intensive fossil energy resources. That view is supported by the IPCC (2018, p. 16) in their special report on "Global Warming of 1.5° C", where they discuss four illustrative pathways of emissions reductions with different projected changes in primary energy from fossil energy resources in 2030 relative to 2010. Averaged across these pathways, the change required in primary energy from coal, gas, and oil is about minus 71 %, plus 6 %, and plus 8 %, respectively.

To date, many countries produce a large share of their electricity from coal. In the EU, about 21.5 % of the fossil energy resources used for generating electricity are still coal resources (Agora Energiewende and Sandbag 2017, p. 7), and many EU citizens and environmental groups are concerned about their governments' reluctance towards, or too slow pace of, phasing out coal. The impression we get from the intensive public discussion about phasing out coal-based electricity generation is that there are policymakers, media and even economists without a clear understanding what the impact of the phase-out policy is when implemented in the prevailing regulatory framework of the EU, which is characterized by the interaction of the climate policies at Union and national level. Our paper aims to identify the distortions such phase-out policies generate on the markets for electricity and permits and it assesses the resulting impact on the countries' welfare.

In a simple static two-country model, we analyze the phase-out policy in the short term when electricity from coal and natural gas is generated under the umbrella of an ETS. Our crucial as well as realistic assumption is that the operating costs of electricity from gas are larger than those from coal and that the emissions intensity of electricity from coal is larger than that from gas. Both countries are price takers on the world markets for coal and gas, for another input, called resource, and for final goods. The markets for electricity and emissions allowances (permits, for short) clear endogenously.

As shown in Table 1, we will analyze phase-out policies along three dimensions.

(i) Electricity may be traded either on national or on international markets. In practice, there is some transboundary trade in electricity, but the cross-border infrastructure is inappropriate and price convergence is partial (European Commission 2017). Our alternative modeling serves to delineate the range of outcomes expected in semi-international

Electricity is traded among ETS countries	Coal-based electricity is phased out		
	by all ETS countries, while the emissions cap is kept constant	by a single ETS country, while the emissions cap is kept constant	tightened
NO	Scenario 1a	Scenario 2a	Scenario 3a
YES	Scenario 1b	Scenario 2b	Scenario 3b

Table 1: Policy scenarios to be analyzed

electricity markets.

(ii) Coal may be phased out either simultaneously in all ETS countries or unilaterally in a single country. Our emphasis is on unilateral phase-out because it involves effects on efficiency and distribution and also because a joint phase-out of ETS countries lacks political support in the EU. The joint phase-out serves as a convenient benchmark.

(iii) Unilateral phase-out of coal may or may not be combined with tightening the emissions cap. In the EU, countries use(d) to phase out coal independent of decisions on (small) reductions of the emissions cap taken on the EU level. It is therefore appropriate to assess the impact of decentral phase-out policies under the assumption that the emissions cap remains unchanged. But we also take up a recent revision of the EU ETS Directive (Directive (EU) 2018/410) providing a phasing-out country with the option to cancel permits from its auction volume to prevent that the decline in its permit demand increases the use of these permits in the other ETS countries.

Since we assume that the emissions cap is binding in the equilibrium of the two-country economy before and after the phase-out policy is applied, it is obvious that the phase-out of coal has no impact on climate damage if the emissions cap remains unchanged. But even if the emissions cap is constant, the phase-out policy has allocative displacement effects on prices of permits and electricity and on the demands and supplies of permits, of electricity from coal and gas and of final goods. We determine the signs of these effects analytically and illustrate the joint equilibria of the markets for permits and electricity before and after the phase-out. The consumption of final goods is our indicator of (consumption) welfare that we use to determine the welfare changes induced by the policy scenarios in Table 1. Although changes in prices and in quantities supplied and demanded for electricity and permits are important in their own right, we restrict our brief preview of results to the welfare effects.

It should not come as a surprise that the phase-out policies of all scenarios reduce

the welfare of the group of ETS countries, because all of them violate the uniform-price requirement for cost-effectiveness. Particularly interesting are the distributional effects in the Scenarios 2 and 3 of unilateral phase-out policies. If the emissions cap is constant and electricity is not traded (Scenario 2a), the unilaterally phasing-out country is worse off and the other countries are better off. The comparative statics of Scenario 2b yields no clear sign of welfare changes because it produces negative and positive partial welfare effects. However, in our calibration the result is as in Scenario 2a: the unilaterally acting country loses and the other country gains.

In the Scenarios 3, the unilateral phase-out of coal affects the countries' consumption welfare - as in the Scenarios 2 -, but in addition it increases the countries' welfare in the form of reduced climate damage. We disregard that additional welfare effect, since it is the same across countries, and find that in qualitative terms the changes in consumption welfare are as in the Scenarios 2. Moreover, our calibrations yield the same signs of the welfare changes in Scenario 3b as in Scenario 3a: the unilaterally acting country loses and the other country gains. That the 'free-riding' country gains - as in the Scenarios 2 - is not an obvious result, since tightening the cap reduces its consumption welfare even if no coal is phased out. In sum, the message is that the country, which phases out coal unilaterally with or without some tightening of the emissions cap, suffers a welfare loss and makes the other country better off regardless of whether electricity markets are national or international.

There is a growing empirical literature on how renewable energy generation has changed the energy generation from coal and gas in the US (Cullen 2013, Novan 2015 and Fell and Kaffine 2018). However, to the best of our knowledge our paper is the first to analyze the phase-out of coal by one or more countries in an EU-type international ETS. When one country phases out coal, coal-based electricity may increase in other countries, and permits and emissions move to other countries. The former phenomenon is known as leakage and the latter as waterbed effect. Leakage is well known in the context of carbon leakage (see e.g. Ishikawa and Kiyono 2006, Fullerton et al. 2014, Böhringer et al. 2017). Waterbed effects have recently received attention in studying the EU ETS (Perino 2018, Eichner and Pethig 2019 and Pahle et al. 2019).

The rest of the paper is organized as follows. Section 2 sets up a stylized two-country model of electricity generation by means of natural gas and coal and CO_2 regulation, and determines the competitive equilibrium. Section 3 analyzes the allocative displacement effects in all policy scenarios listed in Table 1. In Section 4 the model is empirically calibrated and Section 5 concludes.

2 Two countries with ETS and electricity from coal and gas

Production. We consider a two-country economy in which each country $i = A, B$ produces a composite consumption good and electricity in power plants fired either by coal (c-electricity) or by natural gas (g-electricity). The consumption good (quantity supplied x_i^s, quantity demanded x_i^d) is produced by means of electricity input y_i^d and a composite (non-fuel) input r_{xi}, called resource, according to the production function

$$x_i^s = X(y_i^d, r_{xi}) \qquad i = A, B. \tag{1}$$

The production function is increasing[1] ($X_y > 0, X_r < 0$), strictly concave ($X_{yy} < 0, X_{rr} < 0, X_{yy}X_{rr} - X_{yr}^2 < 0$), and electricity and the resource are complements ($X_{ry} > 0$). Since our focus is on the phase-out of c-electricity in an ETS where initially c- and g-electricity is generated, we disregard all other technologies of generating electricity, in particular electricity from renewable energy resources, and take the number of power plants as given.

Electricity (quantity supplied y_{hi}^s) is generated by means of fixed inputs and the variable input coal (quantity f_{ci}) or gas (quantity f_{gi}) according to the production function

$$y_{hi}^s = Y^h(f_{hi}) \qquad h = c, g; \ i = A, B. \tag{2}$$

The production function has the properties $Y^h(0) = 0$, $Y_f^h > 0$ and $Y_{ff}^h \leq 0$. Since the generation of g-electricity is more energy efficient than the generation of c-electricity (De Groot et al. 2017), we assume

$$Y_f^g(f) > Y_f^c(f) \quad \forall f > 0. \tag{3}$$

Denoting by $\check{Y}^h$ the inverse of the function Y^h and by $\bar{p}_{fh}$ the factor price of h-fuel, the (variable) cost of generating h-electricity is $K^h(y_{hi}^s) = \bar{p}_{fh}\check{Y}^h(y_{hi}^s)$. Emissions $E^h(y_{hi}^s)$ from y_{hi}^s units of h-electricity are proportional to the input of fuel used to generate the output y_{hi}^s. Hence we write $E^h(y_{hi}^s) = v_{eh}\check{Y}^h(y_{hi}^s)$, where the constant positive parameter v_{eh} is the emissions released per unit of h-electricity. Due to $v_{ec} > v_{eg}$, (2) and (3) the functions E^h satisfy

$$E^c(y) > E^g(y) \quad \text{and} \quad E_y^c(y) > E_y^g(y) > 0 \quad \forall y > 0. \tag{4}$$

That c-electricity is more emissions intensive than g-electricity is a well-documented empirical fact (MacKay and Stone 2013, p. 4ff.).

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[1] Upper-case letters represent functions and subscripts attached to them indicate partial derivatives.

Markets. Carbon emissions from electricity generation are regulated by an ETS that is jointly operated by the countries A and B. The ETS enforces an emissions cap $\bar{e}$ via auctioning emissions allowances (permits, for short) at the permit price q. The cap $\bar{e}$ is assumed to be binding so that an equilibrium on the permit market requires

$$\bar{e} = E^c(y_{ci}^s) + E^c(y_{cj}^s) + E^g(y_{gi}^s) + E^g(y_{gj}^s) \qquad i, j = A, B; \; i \neq j. \tag{5}$$

The permit price is determined endogenously and so is the price of electricity. Throughout the paper we follow Fischer and Preonas (2010) and Novan (2017) and consider perfectly competitive electricity markets. The decision between assuming either national electricity markets or a single international market is difficult, since it is unclear which of these assumptions is more realistic.

Electricity markets in practice are very complex not least with regard to their interconnectedness. The EU stepped up its efforts over the years to integrate formerly hardly connected national electricity markets, and it made progress through market coupling and investments in cross border interconnections. Currently, electricity is traded among Member States with most exports and imports fluctuating "... in a narrow range of 10% of the total domestic generation" (European Commission 2017, p. 13). That speaks for assuming a single (perfectly competitive) electricity market. However, differences across Member States in wholesale and retail electricity prices across the EU are significant (European Commission 2017) and price convergence is only partial, not least because of inappropriate cross-border infrastructure, coordination and cooperation. These arguments point in direction of national electricity markets.

To cope with the partially integrated empirical electricity markets, we will derive all results alternatively for national electricity markets and for an international electricity market. The pertaining equilibrium conditions are

$$y_{ci}^s + y_{cj}^s + y_{gi}^s + y_{gj}^s = y_i^d + y_j^d \quad i, j = A, B; \; i \neq j \quad \text{and} \quad y_{ci}^s + y_{gi}^s = y_i^s \quad i = A, B \tag{6}$$

for the international market and for the national markets, respectively. Some relief comes from our focus on symmetric countries, however. Due to this simplification the distinction between national and international markets becomes relevant only in Section 3 below in the analysis of unilateral phase-out policies for the following reason. In case of symmetry, the demands and supplies of electricity satisfy $y_{hA}^s = y_{hB}^s = y_h^s$ for $h = c, g$ and $y_A^d = y_B^d = y^d$ such that the equilibrium conditions in (6) simplify to $2y_c^s + 2y_g^s = 2y^d$ and $y_c^s = y_g^s = y^d$, respectively. The associated electricity price is denoted by p_y.

All other goods, i.e. the final good, the resource and h-fuel are traded on world markets at constant prices $\bar{p}_x \equiv 1$, $\bar{p}_r$ and $\bar{p}_{fh}$, respectively.

Demands and supplies. The final goods sector maximizes profits $X(y_i^d, r_{xi}) - \bar{p}_r r_{xi} - p_y y_i^d$. The first-order conditions

$$X_y(y_i^d, r_{xi}) = p_y \quad \text{and} \quad X_r(y_i^d, r_{xi}) = \bar{p}_r \tag{7}$$

yield the factor demand functions

$$y_i^d = D(p_y) \quad \text{with } D_{p_y} < 0 \quad \text{and} \quad r_{xi} = R(p_y) \quad \text{with } R_{p_y} < 0 \quad i = A, B. \tag{8}$$

The profit of electricity sector h is

$$\pi_h = p_y y_{hi}^s - K^h(y_{hi}^s) - q E^h(y_{hi}^s) \qquad h = c, g; \ i = A, B. \tag{9}$$

For any given p_y and q (in the relevant domain), the electricity supply is determined by the first-order condition of profit maximization, $p_y - K_y^h - q E_y^h = 0$. These conditions readily yield the electricity supply functions[2]

$$y_{hi}^s = S^h(p_y, q) \quad \text{with } S_{p_y}^h > 0 \text{ and } S_q^h < 0 \qquad h = c, g; \ i = A, B. \tag{10}$$

Welfare. The representative consumer of country i derives utility from consuming the final good X and suffers from climate damage. We determine the consumption of final goods by considering the consumer's income that consists of all profits plus revenue from selling the resource endowment $\bar{r}$ (owned by the consumer) plus recycled revenue from selling permits. The consumer spends all her income on final goods. In formal terms, the resulting budget equation is equal to[3]

$$x_i^d = X(y_i^d, r_{xi}) + \bar{p}_r(\bar{r} - r_{xi}) + p_y(y_{ci}^s + y_{gi}^s - y_i^d) - K^c(y_{ci}^s) - K^g(y_{gi}^s). \tag{11}$$

For simplicity, we measure consumer i's utility (= country i's welfare) by her consumption of final goods, (11), minus the climate damage caused by both countries' emissions:

$$u_i = x_i^d - H(\bar{e}), \tag{12}$$

where $H(\bar{e})$ is the climate damage satisfying $H' > 0$ and $H'' \geq 0$.

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[2]The properties of the functions $D(p_y)$, $R(p_y)$ and $S^h(p_y, q)$ are derived in Appendix A.

[3]Note also that equation (11) represents the country's trade balance. If electricity markets are national, in (11) the term $p_y(y_{ci}^s + y_{gi}^s - y_i^d)$ is zero.

Joint equilibrium on the markets for permits and electricity. Now we have completed the introduction of the building blocks of the model and proceed with characterizing the equilibrium that results if no phase-out policy is implemented. As argued above, we exploit symmetry and specify the equilibrium on the electricity market(s) simply by $y_c^s + y_g^s = y^d$ keeping in mind that this equation characterizes an equilibrium on national electricity markets as well as on an international electricity market.[4] We combine $y_c^s + y_g^s = y^d$ with (5), (8) and (10) to obtain the joint (symmetric) equilibrium of the markets for permits and electricity,

$$2E^c \left[S^c(p_y, q)\right] + 2E^g \left[S^g(p_y, q)\right] = \bar{e} \quad \text{and} \quad S^c(p_y, q) + S^g(p_y, q) = D(p_y). \tag{13}$$

Suppose the prices (p_{y0}, q_0) satisfy both equations in (13) when the emissions cap $\bar{e} = \bar{e}_0$ is given. Then the point $\mathcal{S}_0$ in Figure 1 illustrates the equilibrium on the electricity market if we make the assignments $C_0 D_0 \hat{=} S^g(p_y, q_0)$, $E_0 F_0 \hat{=} S^c(p_y, q_0) + S^g(p_y, q_0)$, $GH \hat{=} D(p_y)$, (while disregarding the dashed curve $E_1 F_1$).
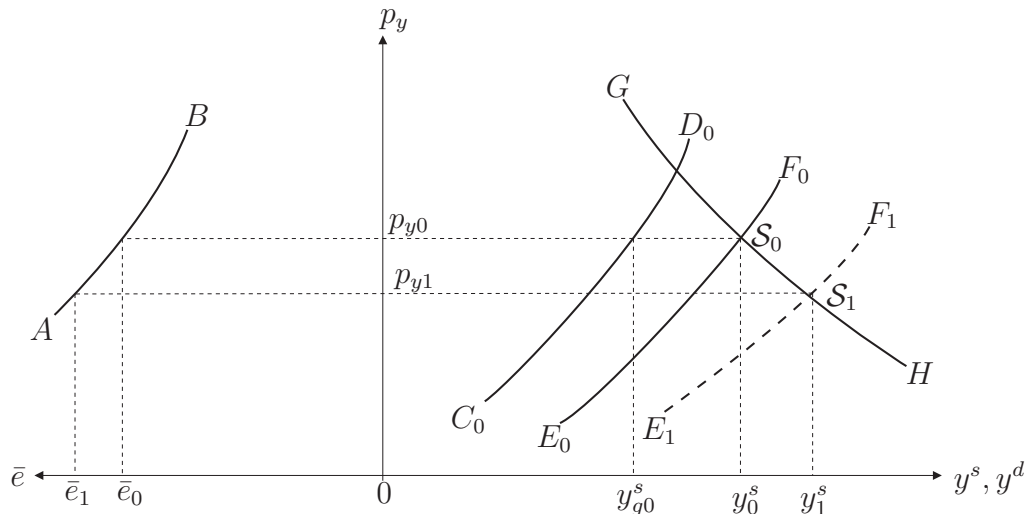
Figure 1: Joint equilibrium of the permit market and the electricity markets depending on the size of the emissions cap

Suppose next the emissions cap is relaxed from $\bar{e}_0$ to $\bar{e}_1 > \bar{e}_0$. In order to restore the equilibrium on the permit market, it is necessary to increase emissions through increasing the generation of electricity. Expanding the electricity supply would create an excess supply of electricity unless the electricity demand increases too. The demand increases if and only if the electricity price declines.[5] Therefore, there is a price $p_{y1} < p_{y0}$ and a permit price q_1

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[4]This equivalence clearly breaks down if the technologies of producing final goods and electricity differ across countries. As will be shown below, it also breaks down when the (otherwise symmetric) countries pursue different energy policies.

[5]We prove in Appendix A that the equilibrium electricity price is declining in the emissions cap.

which satisfy

$$2E^c\left[S^c(p_{y1}, q_1)\right] + 2E^g\left[S^g(p_{y1}, q_1)\right] = \bar{e}_1 \quad \text{and} \quad S^c(p_{y1}, q_1) + S^g(p_{y1}, q_1) = D(p_{y1}).$$

In order to specify the change in the permit price we totally differentiate the second equation in (13) and find that the permit price must decline along with the electricity price, i.e. $q_1 < q_0$. To illustrate the increase in the emissions cap from $\bar{e}_0$ to $\bar{e}_1 > \bar{e}_0$ in Figure 1 we replace the aggregate electricity supply curve $E_0 F_0$ by the dashed curve $E_1 F_1$ which intersects the electricity demand curve GH at the new equilibrium point $\mathcal{S}_1$. Hence we observe the expected result that the less stringent the emissions cap, the lower the prices of permits and electricity and the larger the aggregate generation of electricity.

We presupposed that the electricity supply is a mix of c- and g-electricity in the initial equilibrium (p_{y0}, q_0), and we found that this is also true after the emissions cap is relaxed from $\bar{e}_0$ to $\bar{e}_1 > \bar{e}_0$. Furthermore, in Appendix A we prove that if we consider an initial equilibrium in which both c- and g-electricity is supplied and if we then successively tighten the emissions cap, the share of g-electricity rises and that of c-electricity declines. We conclude that there is some (high) permit price $\mathring{q}$ such that the supply of c-electricity is fully crowded out if and only if $q \geq \mathring{q}$.

3   Policies of phasing out coal

As discussed in the introduction, environmental groups are increasingly pressing for phasing out coal-fired power plants on the grounds that c-electricity is 'dirtier' than g-electricity. Some countries participating in the EU ETS make plans - or have already taken action - on substituting c-electricity with g-electricity, be it in response to lobbying pressure or in an effort to reach self-determined national and/or EU emissions targets. These observations call for investigating the impact of policies that substitute c- with g-electricity.

Currently, in many countries the electricity supply consists of a mix of c- and g-electricity. Hence we assume that the emissions cap in our two-country economy is such that the c- and g-electricity is supplied in the resulting (initial) equilibrium. Suppose both countries in our model decide to phase out the generation of c-electricity completely. One way to reach that goal is to tighten the emissions cap so strongly that c-electricity becomes unprofitable and phases out without further regulatory action. As shown at the end of the last section, successive reductions of the emissions cap would raise the prices for electricity and permits and would reduce the share of c-electricity until that share is zero. That

substantial reductions in the generation of c-electricity can be achieved by raising the permit price has recently been demonstrated in the UK. According to Agora Energiewende and Sandbag (2017, p. 22), the UK doubled its carbon price support in 2015 to 18 $\frac{£}{t\,CO_2}$ on top of the (low) EU permit price. As a result, the generation of c-electricity decreased by 44 TWh and the generation of g-electricity increased by 45 TWh. These changes in the UK are of about the same order than the sum of the changes in all other EU countries.

The strategy of raising the carbon price would indeed be necessary in the EU ETS to reach the Paris climate goal *cost-effectively*. Environmental economists keep emphasizing that a necessary condition for the cost-effective implementation of the Paris climate goal is a carbon price (here in the form of the permit price) that is uniform across countries. The carbon price, which does that job if applied worldwide, is estimated to be about 65 $\frac{€}{t\,CO_2}$ by 2020 and rising to 85 $\frac{€}{t\,CO_2}$ by 2030 (Stiglitz and Stern 2017). In contrast, the permit price in the EU ETS currently is about 20 $\frac{€}{t\,CO_2}$. If the EU would tighten the emissions cap so strongly that the permit price rises to 65 $\frac{€}{t\,CO_2}$ or even to 85 $\frac{€}{t\,CO_2}$, the generation of c-electricity would presumably be unprofitable and would therefore be not supplied anymore.

Policymakers use to have strong incentives to keep the prices of electricity and permits low for political-economic reasons such as myopia or the concern for low income groups that would be hit hard by high prices for electricity ('energy poverty') or the concern for industries that would face higher costs and become less competitive in the world market. It is an empirical fact that the strong tightening of the emissions cap necessary to make it consistent with cost-effective implementation of the Paris goal lacks the necessary unanimous support in the EU ETS. More generally, the cost-effective global solution to the climate change problem via a worldwide uniform carbon price appears to be politically infeasible. If policymakers make an effort to phase out the 'dirtiest' generation of electricity, they tend to resort to second-best policies that phase out the generation of c-electricity by 'command and control'.

Before we proceed with analyzing some scenarios of phasing out coal by regulation, it is helpful to clarify without reference to market equilibria how a country's emissions change when it fully replaces the c-electricity it has phased out with additional g-electricity. Suppose a country generates the amounts y_c^s and y_g^s of c- and g-electricity that add up to $y_0^s = y_c^s + y_g^s$. We wish to determine the conditions under which the emissions $E^c(y_c^s)$ released from generating c-electricity before the phase-out are larger or smaller than the emissions $E^g(y_0^s) - E^g(y_g^s)$ released after the phase-out from generating the extra quantity $y_g^s - y_0^s$ of g-electricity. In Appendix A, we prove that $E^g(y_0^s) - E^g(y_0^s - y_c^s) < E^c(y_c^s)$ for all $y_c^s \in [0, y_0^s]$

under the conditions

$$E_y^c(y_c^s) > E_y^g(y_0^s - y_c^s) \quad \forall \, y_c^s \in [0, y_0^s] \quad \text{and} \quad y_0^s < \tilde{y}, \tag{14}$$

where $\tilde{y}$ is defined by $E_y^c(0) = E_y^g(\tilde{y})$. Essentially, (14) puts an upper bound on total electricity generation for any given electricity generation technology.[6] In our subsequent analysis of phase-out policies, we will focus on economies where the constraint (14) holds in addition to the conditions introduced in (3) and (4).

Section 3.1 analyzes the Scenarios 1a and 1b of Table 1, in which the countries A and B jointly phase out the generation of c-electricity, while the emissions cap remains unchanged. In Section 3.2, we keep the emissions cap constant, but country A phases out coal unilaterally (Scenarios 2a and 2b). Finally, Section 3.3 deals with the Scenarios 3a and 3b of Table 1 in which country A's unilateral phase-out policy is combined with some tightening of the emissions cap as suggested in a recent revision of the EU ETS Directive.

3.1 Joint phase-out of coal

Since the countries are symmetric in the equilibrium before the phase-out of coal and implement the same policies of phasing out c-electricity, they will remain symmetric after the phase-out. Hence, the allocative displacement effects of the phase-out are the same when the electricity markets are national (Scenario 1a) or international (Scenario 1b). We prove in Appendix B

Proposition 1.
Suppose the initial equilibrium of the economy is characterized by a mix of c- and g-electricity, and both countries phase out the generation of electricity from coal while leaving the emissions cap unchanged. The pertaining comparative-static effects are presented in Table 1.

In order to discuss the effects of the joint phase-out policy summarized in Proposition 1, we recall that there is a symmetric equilibrium on the markets for electricity and permits

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[6]The relation between the constraint $y_0^s < \tilde{y}$ and the technology can be conveniently made explicit by specifying the emissions functions by $E^h(y_h^s) = a_h y_h^s + b(y_h^s)^2$ for $h = c, g$. In that parametric version of the functions E^h the condition $y_0^s < \tilde{y}$ from (14) is converted into $y_0^s < (a_c - a_g)/2b$. Inspection of that inequality reveals that the technological constraint on y_0^s is the weaker, the larger is the difference between the emissions intensities of c- and g-electricity, $(a_c - a_g \uparrow)$, and the less progressively increasing are the emissions in electricity output $(b \downarrow)$.

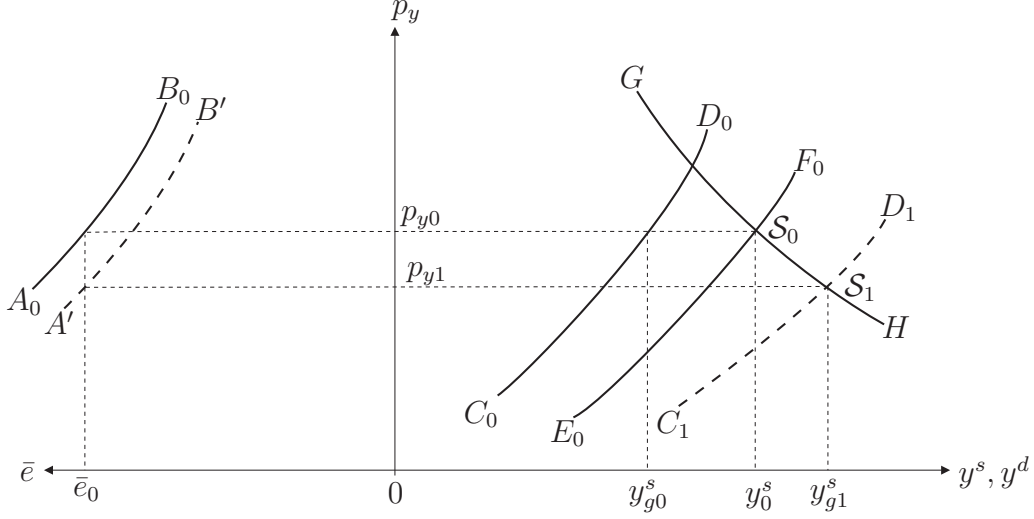|	$\mathrm{d}y_g^s$	$\mathrm{d}y^d$	$\mathrm{d}r_x$	$\mathrm{d}p_y$	$\mathrm{d}q$	$\mathrm{d}x^s$	$\mathrm{d}x^d$
$\mathrm{d}\bar{y}_c^s < 0$	$+$	$+$	$+$	$-$	$-$	$+$	$-$

Table 2: Allocative impact of Scenario 1

Figure 2: Phase-out of coal in both countries

before coal is phased out. We define $S^h(p_{y0}, q_0) =: y_{h0}^s$, $D(p_{y0}) =: y_0^d$ for $i = A, B$ and $h = c, g$ and characterize that initial equilibrium by (p_{y0}, q_0) and

$$y_{c0}^s + y_{g0}^s = y_0^d \quad i = A, B \quad \text{and} \quad 2E^c(y_{c0}^s) + 2E^g(y_{g0}^s) = \bar{e}_0. \tag{15}$$

In Figure 2, the solid curves are the same as in Figure 1 so that $\mathcal{S}_0$ is the equilibrium before the phase-out of coal specified in (15).

To understand how the new equilibrium after the phase-out comes about, suppose both countries did phase-out coal but the initial prices (p_{y0}, q_0) still prevail. Then the electricity market is in excess demand and the permit market is in excess supply. Suppose next, both countries exactly replace the former c-electricity output by g-electricity such that their new total output of g-electricity is equal to y_0^d. Consequently, the electricity market is in equilibrium (again) at point $\mathcal{S}_0$ in Figure 2 but the permit market is still in excess supply because we presupposed (14) to hold. In order to clear the permit market, both countries have to increase their g-electricity beyond y_0^d without creating a disequilibrium on the electricity market. To accomplish that they need to depart from point $\mathcal{S}_0$ and move on the demand curve GH in the direction of H. That can and must be done by an appropriate simultaneous reduction of the prices for permits and electricity until some prices (p_{y1}, q_1), $p_{y1} < p_{y0}$, $q_1 < q_0$, are attained such that $y_{g1}^s = S^g(p_{y1}, q_1)$, $y_1^d = D(p_{y1})$, $y_{g1}^s = y_1^d > y_0^d$, and $2E^g(y_{g1}^s) = \bar{e}_0$. In Figure 2 each country's new equilibrium is illustrated by point $\mathcal{S}_1$, where

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the demand curve GH intersects the dashed curve C_1D_1, which is the graph of the supply function $S^g(p_y, q_1)$.

The comparison of the initial allocation $(p_{y0}, q_0, y_0^d, y_{c0}^s, y_{g0}^s, y_0^s)$ with the final allocation $(p_{y1}, q_1, y_1^d, y_{c1}^s, y_{g1}^s, y_1^s)$ in Figure 2 reveals - as it should - that the increases or decreases of equilibrium variables are consistent with Table 2.

Table 2 shows that the impact of the phase-out policy on the joint equilibrium of the markets for permits and electricity has important consequences for the supply of and demand for final goods. The production of final goods rises $(\mathrm{d}x^s > 0)$ due to larger inputs of electricity $(\mathrm{d}y^d > 0)$ and resources $(\mathrm{d}r_x > 0)$. The increase in the production of final goods may be interpreted as a benefit of the phase-out policy. However, according to Proposition 1 greater production goes along with less consumption of final goods $(\mathrm{d}x^d < 0)$. Since consumption of final goods is our measure of welfare, the phase-out policy is welfare reducing. The reason for the negative net effect on final goods consumption (= consumption welfare) is the sacrifice of low-cost c-electricity for higher-cost g-electricity.

It is interesting to explain from a different perspective why the phase-out policy is welfare reducing. Suppose the equilibrium (p_{y0}, q_0) in Figure 2 prevails, and governments prevent the generation of c-electricity by intervening in the permit market as follows. (i) For the firms generating c-electricity they fix the permit price at a level $\mathring{q}$, which is high enough to render the generation of c-electricity unprofitable. (ii) The firms generating g-electricity auction permits, as before, and the electricity price remains unregulated as well. The obvious result is that no c-electricity is generated at all and hence the equilibrium point $\mathcal{S}_1$ will be attained in Figure 2. Thus, we have an equilibrium with prices $(p_{y1}, q_1, \mathring{q})$, and all prices are distorted: $p_{y1} < p_{y0}$ and $\mathring{q} > q_0 > q_1$. The raison d'être of an ETS is to bring forth a uniform emissions price that secures cost-effectiveness by equalizing the marginal abatement costs of all firms covered by the ETS. In contrast, the phase-out policy is equivalent to creating differentiated permit prices and thus perverts the concept of an ETS by eliminating the unique advantage it is designed to offer, namely cost-effective abatement.

3.2 Unilateral phase-out of coal without changing the emissions cap

In line with the subsidiarity principle, EU countries pursue different approaches with respect to developing and regulating their domestic energy sector, and they follow different strategies of using coal and gas to generate electricity. Some countries participating in the EU ETS have already phased out coal, in some countries a phase-out is under discussion, and others

do not even discuss a phase-out. Countries with major shares of coal face increasing pressure to reduce that share, as e.g. Germany, where mitigation activists recently underlined their demands for phasing out the particularly dirty lignite-fired power plants with actions of great publicity and media coverage. These observations give rise to the question, what the impact will be, if an individual ETS country phases out coal unilaterally.

National electricity markets (Scenario 2a). In Appendix C we have performed the comparative statics of country A's unilateral reduction of the generation of c-electricity.

Proposition 2.
Suppose the initial equilibrium of the two-country economy with national electricity markets is characterized by a mix of c- and g-electricity and country A phases out the generation of electricity from coal unilaterally, while the emissions cap remains unchanged. If the convexity of the functions K^c and E^c is sufficiently weak, the pertaining comparative-static effects are as presented in Table 3.

		$\mathrm{d}y^s_{gA}$	$\mathrm{d}y^d_A$	$\mathrm{d}r_{xA}$	$\mathrm{d}p_{yA}$	$\mathrm{d}q$	$\mathrm{d}x^s_A$	$\mathrm{d}x^d_A$
$\mathrm{d}\bar{y}^s_{cA} < 0$		$+$	$-^{\dagger}$	$-$	$+^{\dagger}$	$-$	$-$	$-$
	$\mathrm{d}y^s_{cB}$	$\mathrm{d}y^s_{gB}$	$\mathrm{d}y^d_B$	$\mathrm{d}r_{xB}$	$\mathrm{d}p_{yB}$	$\mathrm{d}q$	$\mathrm{d}x^s_B$	$\mathrm{d}x^d_B$
$\mathrm{d}\bar{y}^s_{cA} < 0$	$+$	$-$	$+$	$+$	$-$	$-$	$+$	$+$

† holds if $E^c_y(y^s_c) > 2E^g_y(y^s_0 - y^s_c)$ for all $y^s_c \in [0, y^s_0]$

Table 3: Allocative impact of Scenario 2a

In Scenario 2a the readjustments on the markets for permits and electricity are more complex than in Scenario 1, because the unilateral policy creates asymmetries that were absent in Scenario 1. Figure 3 is useful for understanding the economic drivers of the reallocation. The solid curves are the same as in the previous figures and so the intersection point $\mathcal{S}_0$ illustrates the initial symmetric equilibrium with prices (p_{y0}, q_0) in both panels of Figure 3. We assume that the equilibrium (15) is disturbed by country A's complete phase-out of c-electricity and now discuss the re-adjustments of prices and quantities in several steps.

(i) Suppose first the initial equilibrium prices (p_{y0}, q_0) remain unchanged after country A phased out the generation of c-electricity. Then the electricity market in B is still in equilibrium, $y^s_{c0} + y^s_{g0} = y^d_0$, but there is an excess demand for electricity in A, $y^s_{g0} < y^d_0$, which implies that the permit market is in excess supply, $E^c(y^s_{c0}) + 2E^g(y^s_{g0}) < \bar{e}_0$.
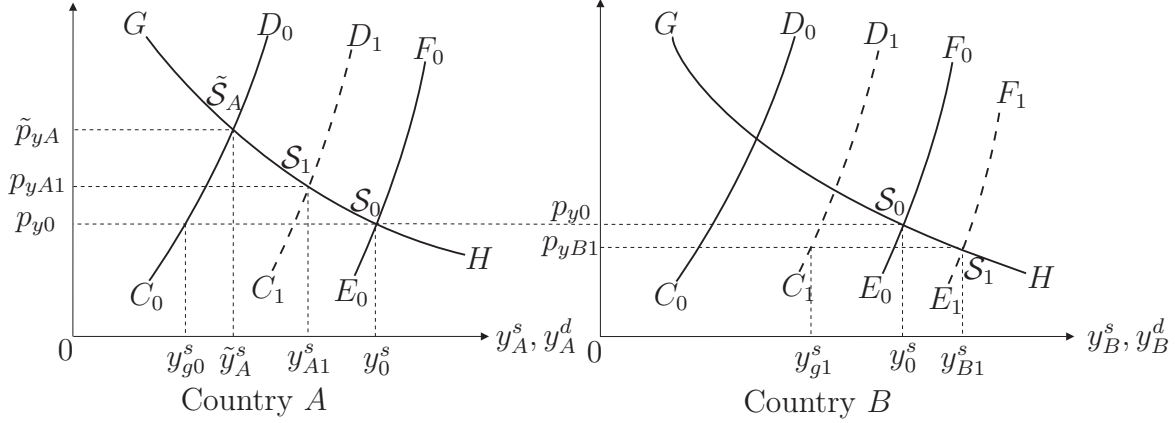
Figure 3: Readjustments in the national electricity markets in Scenario 2a

(ii) Next, keep q constant at the level q_0, but let p_y adjust as to clear the electricity markets. The electricity market equilibrium in B continues to prevail at price p_{y0}, while in A the price p_y rises up to some $\tilde{p}_{yA} > p_{y0}$ defined by the equilibrium condition $S^g(\tilde{p}_{yA}, q_0) = D(\tilde{p}_{yA})$. This equilibrium corresponds to the point $\tilde{S}_A$ in the left panel of Figure 3. Since $y_{g0}^s < S^g(\tilde{p}_{yA}, q_0) < y_0^d$, it follows that $S^g(\tilde{p}_{yA}, q_0) + y_{c0}^s + y_{g0}^s = S^g(\tilde{p}_{yA}, q_0) + y_0^d < 2y_0^d$. Due to assumption (14) the permit market is still in excess supply, $E^g\left[S^g(\tilde{p}_{yA}, q_0) + E^c(y_{c0}^s) + E^g(y_{c0}^s)\right] < \bar{e}_0$.

(iii) Finally, we take the electricity market equilibria $\tilde{S}_A$ and S_0 as our points of departure. The task is to increase the generation of electricity in each country while keeping the electricity markets in equilibrium. The only way to accomplish that is to reduce simultaneously the prices of both permits *and* electricity. Through that price adjustment strategy we reach the prices $q_1 < q_0$, $p_{yA1} < \tilde{p}_{yA}$ and $p_{yB1} < p_{y0}$ satisfying the equilibrium conditions $D(p_{yA1}) = S^g(p_{yA1}, q_1)$, $D(p_{yB1}) = S^c(p_{yB1}, q_1) + S^g(p_{yB1}, q_1) > y_0^d$, and $E^g\left[S^g(p_{yA1}, q_1)\right] + E^c\left[S^c(p_{yB1}, q_1)\right] + E^g\left[S^g(p_{yB1}, q_1)\right] = \bar{e}_0.$[7]

Scenario 2a differs remarkably from Scenario 1, because the economies of the countries A and B move in opposite directions. While country A phases out the generation of c-electricity, country B increases the generation of c-electricity, $S^c(p_{yB1}, q_1) > y_{c0}^s$, which makes the net reduction of c-electricity in the two-country economy smaller than the amount y_{c0}^s country A phased out. Country A's phase-out policy generates a waterbed effect of emissions, since each country released $\bar{e}_0/2$ emissions before the phase-out, but after that country A's emissions e_{A1} are smaller than country B's emissions e_{B1}, $e_{A1} < \bar{e}_0/2 < e_{B1}$. As Proposition 2 shows, the inputs of electricity and the resource in the production of final

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[7]The (positive) difference $\tilde{p}_{yA} - p_{yA1}$ is the smaller the more progressive is the increase of emissions when the electricity output increases. We provide conditions for $p_{yA1} > p_{y0}$ in Table 3.

goods are larger in country B than in country A, and consequently the final goods production is larger in country B than in country A. Of all effects pointing in opposite directions, the most significant one is that country A suffers a welfare loss whereas country B is better off. Observe also that country A's loss is greater than country B's welfare gain, because the phase-out policy is distortionary.

To improve the understanding of these welfare implications, reconsider the initial symmetric equilibrium with prices (p_{y0}, q_0), in which each country releases the emissions $\bar{e}_0/2$, and suppose there is no joint ETS but each country operates a national ETS in which the emissions caps are fixed at $\bar{e}_A = \bar{e}_B = \bar{e}_0/2$. Then the equilibrium allocation with two national ETSs is the same as in case of the joint ETS. Next, realign the national emissions caps by setting $\bar{e}_A = e_{A1} < \bar{e}_0/2$ and $\bar{e}_B = e_{B1} > \bar{e}_0/2$, where e_{A1} and e_{B1} are the countries' emissions after the phase-out in the Scenario 2a (referred to in the last paragraph and satisfying $e_{A1} + e_{B1} = \bar{e}_0$). If country A does not phase out coal in this scenario with national ETSs, the tighter emissions cap reduces country A's welfare and the laxer emissions cap enhances country B's welfare. If country A phases out coal, country B is unaffected and is therefore still better off with the cap $\bar{e}_B = e_{B1}$ than with the cap $\bar{e}_B = \bar{e}_0/2$. In contrast, when the emissions cap is $\bar{e}_A = e_{A1}$, country A is worse off after the phase-out than before, because it dispensed with c-electricity. Put differently, country A loses twice, due to the reduced emissions (resp. the tightened emissions cap) and due to the distortion created by the phase-out.

That its unilateral phase-out policy makes country A worse off and country B better off seems to be at variance with common sense which suggests that phasing out the dirtiest technology of generating electricity is always a desirable and necessary measure to fight climate change. It is counter-intuitive that a country loses when it unilaterally phases out c-electricity, but it is even harder to accept that its phase-out policy enhances the welfare of inactive 'free-riding' countries. Nevertheless, the economic rationale of the perverse welfare effects is clear. They follow from allocative distortions created by emissions-reducing *national* measures within the institutional framework of an ETS encompassing more than one country.

International electricity market (Scenario 2b).   In Appendix D, we have performed the comparative statics of country A's unilateral reduction of the generation of c-electricity.

Proposition 3.
Suppose the initial equilibrium of the two-country economy with an international electricity market is characterized by a mix of c- and g-electricity and country A phases out the gener-

ation of electricity from coal unilaterally, while the emissions cap remains unchanged. If the convexity of the functions K^g and E^g is sufficiently weak, the pertaining comparative-static effects are as presented in Table 4.

		dy^s_{gA}	dy^d_A	dr_{xA}	dp_y	dq	dx^s_A	dx^d_A
$d\bar{y}^s_{cA} < 0$		$+$	$+$	$+$	$-$	$-$	$+$	?
	dy^s_{cB}	dy^s_{gB}	dy^d_B	dr_{xB}	dp_y	dq	dx^s_B	dx^d_B
$d\bar{y}^s_{cA} < 0$	$+$	$+$	$+$	$+$	$-$	$-$	$+$	?

Table 4: Allocative impact of Scenario 2b

We explain the transition of the initial prices (p_{y0}, q_0) to the new equilibrium prices (p_{y1}, q_1) in Scenario 2b in several steps.

(i) Set $y^s_{cA} = 0$ and suppose that (p_{y0}, q_0) still prevails. Then $S^c(p_{y0}, q_0) + 2S^g(p_{y0}, q_0) < D(p_{y0})$ and $E^c[S^c(p_{y0}, q_0)] + 2[S^g(p_{y0}, q_0)] < \bar{e}_0$.

(ii) Leave p_{y0} unchanged and choose $q = q'$ such that the electricity market clears, $S^c(p_{y0}, q') + 2S^g(p_{y0}, q') = D(p_{y0})$. It is clear that $S^h(p_{y0}, q') > S^h(p_{y0}, q_0)$ for[8] $h = c, g$ and therefore $E^c[S^c(p_{y0}, q')] + 2[S^g(p_{y0}, q')] > E^c[S^c(p_{y0}, q_0)] + 2[S^g(p_{y0}, q_0)]$, but the sign of $E^c[S^c(p_{y0}, q')] + 2[S^g(p_{y0}, q')] - \bar{e}_0$ is unclear.

(iii) Assume that the second derivatives E^h_{yy} are positive but small enough such that

$$E^c[S^c(p_{y0}, q')] + 2[S^g(p_{y0}, q')] < \bar{e}_0. \tag{16}$$

(iv) In view of (16) clearance of the electricity market requires increasing the supply of electricity. If we would do that by decreasing the permit price while keeping p_{y0} constant, we would create an excess supply on the electricity market. Hence we have to reduce both the permit price and the electricity price in such a way that both markets clear simultaneously. Summing up, the new equilibrium prices (p_{y1}, q_1) satisfy $p_{y1} < p_{y0}$ and $q_1 < q_0$.

Figure 4 illustrates the allocative displacement effects of country A's phase-out policy in the markets for permits and electricity. The solid curves are the same as in the previous figures, $\mathcal{S}_0$ characterizes the equilibrium before A implements the phase-out policy, and $\bar{e}_0$ is the emissions cap that remains unchanged. Figure 4 shows that the signs of the changes in prices and supply of g-electricity are $p_{y1} - p_{y0} < 0$, $q_1 - q_0 < 0$, and $y^s_{g1} - y^s_{g0} > 0$.

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[8]Country B's generation of c-electricity also increases as we showed for the case of relaxing the cap without phasing out coal at the end of Section 2.
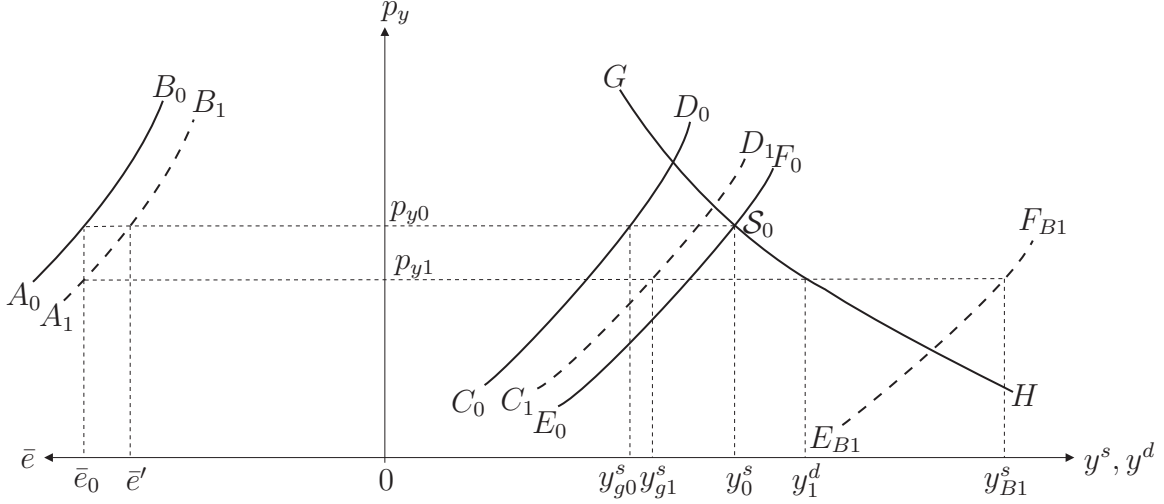
Figure 4: Readjustments in the international electricity market in Scenario 2b

The increase of g-electricity generation is illustrated by the shift of the g-electricity supply curve from $C_0 D_0$ to $C_1 D_1$. Since both countries use the same technology, they produce the same amount $y_{gA1}^s = y_{gB1}^s = y_{g1}^s$ of g-electricity. After the phase-out, the permits initially used by country A for the generation of c-electricity are relocated as follows. Each country buys a share of the idle permits to increase the generation of g-electricity, and country B uses the remaining permits to increase the generation of c-electricity ($y_{cB1}^s > y_{c0}^s$). Country B's total electricity supply curve after the phase-out is depicted in Figure 4 by the dashed curve $E_{B1} F_{B1}$. Since the new equilibrium electricity price is p_{y1}, country A's total electricity supply is $y_{A1}^s = y_{g1}^s$, and country B's total electricity generation is $y_{B1}^s = y_{g1}^s + y_{cB1}^s$. The quantity y_{B1}^s is larger than y_0^s not only because $y_{gB1}^s > y_{g0}^s$, but also because $y_{cB1}^s > y_{c0}^s$. Hence the net reduction of c-electricity in the two-country economy is $y_{c0}^s - (y_{cB1}^s - y_{c0}^s)$, which is positive but less than the c-electricity y_{c0}^s phased out by country A.

In Figure 4, y_{B1}^s exceeds y_{A1}^s by $\Delta y_B^s = y_{cB1}^s + y_{gB1}^s - y_{gA1}^s = y_{cB1}^s > 0$. Since after the phase-out the demand for electricity, $Y^d(p_{y1})$, is the same in both countries, country B exports - and country A imports - $\frac{1}{2}\Delta y_B^s$ units of electricity. Since both countries generate the same amount of g-electricity, country A's electricity import can be interpreted as replacing, to some extent, its former c-electricity generation by an import of c-electricity. The counterpart of the changes in supplies and demands of electricity caused by the phase-out are changes in the purchase of permits. Specifically, country A buys $\Delta e_A = \left| w_c y_{c0}^s - w_g (y_{gA1}^s - y_{g0}^s) \right|$ permits less after the phase-out than before and country B increases its purchase of permits by Δe_A. Therefore, the cross-border trade of electricity implies a waterbed effect of permits and emissions. Put differently, country A's unilateral phase-out policy reduces *domestic*

emissions significantly, but it does so at the expense of a leakage rate of 100 percent.

An intriguing difference between modeling electricity markets as national (Scenario 2a) or international (Scenario 2b) is that in the case of an international electricity market we discuss here the comparative statics do not yield an unambiguous sign of the welfare changes in the countries A and B. It is clear that the aggregate welfare declines (in both Scenario 2a and 2b) and our strong conjecture is that country A loses as in case of national markets. The ambiguity arises from cross-border electricity trade that generates partial effects with different signs in the comparative statics of Scenario 2b.

3.3 Unilateral phase-out of coal with tightening the emissions cap

Now we assume that country A phases out coal, as in Scenario 2, and combines that policy with reducing the emissions cap by the amount of permits it purchased to cover the generation of c-electricity before the phase-out of coal. This scenario is inspired by the recent revision of the EU ETS Directive (Directive (EU) 2018/410) that entered into force on 8 April 2018 and will apply for the period 2021-2030. Specifically, the revised EU Directive stipulates that recognizing "... the interaction between climate policies at Union and national level, Member States should have the possibility of cancelling allowances from their auction volume in the event of closures of electricity-generation capacity in their territory."

Conceptually, the Scenario 3 can be decomposed into two parts. The first is the phase-out policy of Scenario 2, and the second part is the tightening of the emissions cap, which yields a benefit in the form of reduced climate damage. Since that climate benefit is the same across countries (due to the additivity of the welfare function (12)), we disregard it and restrict our focus instead to the consumption of final goods that we refer to as consumption welfare.[9]

National electricity markets (Scenario 3a). Suppose country A complements its unilateral phase-out policy of scenario 2 with cutting back the initial emissions cap from $\bar{e}_0$ to $\bar{e}_1 \equiv \bar{e}_0 - E^c(\bar{y}_{c0}^s)$, where $\bar{y}_{c0}^s$ is its generation of c-electricity before phasing out coal. The comparative statics of a marginal reduction in the generation of c-electricity, $\mathrm{d}\bar{y}_{cA}^s < 0$, combined with a marginal reduction of the emissions cap, $\mathrm{d}\bar{e} = E_y^c \mathrm{d}\bar{y}_{cA}^s < 0$, is carried out in Appendix E. We summarize the results in

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[9]Observe that in the Scenarios 2a and 2b consumption welfare and aggregate welfare coincide since the emissions cap - and hence the climate damage is unchanged.

Proposition 4.

Suppose the initial equilibrium of the two-country economy with national electricity markets is characterized by a mix of c- and g-electricity, country A phases out the generation of electricity from coal unilaterally and cancels its emissions allowances formerly used for the generation of c-electricity. If the convexity of the functions K^c and E^c is sufficiently weak, the pertaining comparative-static effects are as presented in Table 5.

		$\mathrm{d}y_{gA}^s$	$\mathrm{d}y_A^d$	$\mathrm{d}r_{xA}$	$\mathrm{d}p_{yA}$	$\mathrm{d}q$	$\mathrm{d}x_A^s$	$\mathrm{d}x_A^d$
$\mathrm{d}\bar{y}_{cA}^s < 0$		$+$	$-$	$-$	$+$	$+$	$-$	$-$
	$\mathrm{d}y_{cB}^s$	$\mathrm{d}y_{gB}^s$	$\mathrm{d}y_B^d$	$\mathrm{d}r_{xB}$	$\mathrm{d}p_{yB}$	$\mathrm{d}q$	$\mathrm{d}x_B^s$	$\mathrm{d}x_B^d$
$\mathrm{d}\bar{y}_{cA}^s < 0$	$-$	$+$	$-$	$-$	$+$	$+$	$-$	$-$

Table 5: Allocative impact of Scenario 3a

Analogous to our procedure in Scenario 2a, we explain the allocative displacement effects on the markets for permits and electricity in several steps.

(i) Suppose first the generation of c-electricity drops to zero in A, the emissions cap is reduced from $\bar{e}_0$ to $\bar{e}_1$, and the initial equilibrium prices (p_{y0}, q_0) remain unchanged. Then the electricity market in B is still in equilibrium, $y_{c0}^s + y_{g0}^s = y_0^d$, but there is an excess demand for electricity in A, $y_{g0}^s < y_0^d$. Since the cap is reduced exactly by the amount of permits formerly purchased by A for the generation of y_{c0}^s units of c-electricity, the permit market is still in equilibrium, $E^c(y_{c0}^s) + 2E^g(y_{g0}^s) = \bar{e}_1$.

(ii) Next keep q constant at the level q_0, but let p_y adjust as to clear the electricity markets. The electricity market equilibrium in A continues to prevail at price p_{y0}, while in B the price p_y rises up to some $\tilde{p}_{yA} > p_{y0}$ defined by the equilibrium condition $S^g(\tilde{p}_{yA}, q_0) = D(\tilde{p}_{yA})$. This equilibrium corresponds to the point $\tilde{\mathcal{S}}_A$ in the left panel of Figure 3. Since $S^g(\tilde{p}_{yA}, q_0) > y_{g0}^s$, it follows that now the permit market is in excess demand, $E^c(y_{c0}^s) + E^g(y_{g0}^s) + E^g[S^g(\tilde{p}_{yA}, q_0)] > \bar{e}_1$.

(iii) Finally, suppose the state of the two-country economy is given by the points $\tilde{\mathcal{S}}_A$ and $\mathcal{S}_0$ that represent equilibria on the national electricity markets in Figure 3. The task is to reduce the generation of electricity in each country while keeping the electricity markets in equilibrium. The only way to accomplish that is to increase simultaneously the prices of both permits *and* electricity. Through that price adjustment strategy we reach the prices $q_1 > q_0$, $p_{yB1} > p_{y0}$ and $p_{yA1} > \tilde{p}_{yA}$ satisfying the equilibrium conditions $D(p_{yA1}) = S^g(p_{yA1}, q_1) < y_0^d$, $D(p_{yB1}) = S^c(p_{yB1}, q_1) + S^g(p_{yB1}, q_1) < y_0^d$ and $E^g[S^g(p_{yA1}, q_1)] + E^c[S^c(p_{yB1}, q_1)] +$

$E^g\left[S^g(p_{yB1}, q_1)\right] = \bar{e}_1.$

In the new joint equilibrium of the markets for permits and electricity with prices (p_{yA1}, p_{yB1}, q_1) both countries' emissions are smaller than $\bar{e}_0/2$. This is the reason why the consumption welfare declines in both countries ($\mathrm{d}x_A^d < 0$, $\mathrm{d}x_B^d < 0$ in Proposition 4). In country A, the loss of consumption welfare is more severe in Scenario 3a than in 2a, because A's emissions decrease more strongly in 3a than in 2a. While the permit price decreases in Scenario 2a, it increases in Scenario 3a which indicates that the reduction of the emissions cap by $\Delta\bar{e} = E^c(y_{c0}^s)$ effectively raises the price of emissions, as is necessary for fighting climate change. It is also clear, however, that if the emissions cap is tightened by an amount smaller than $E^c(y_{c0}^s)$, the difference of the outcomes of the Scenarios 2a and 3a shrinks, and it becomes the smaller, the smaller the emissions cap reduction.

International electricity market (Scenario 3b). The comparative statics of a marginal reduction in country A's generation of c-electricity combined with a marginal reduction of the emissions cap is carried out in Appendix F. We list the results in

Proposition 5.

Suppose the initial equilibrium of the two-country economy with an international electricity market is characterized by a mix of c- and g-electricity, country A phases out the generation of electricity from coal unilaterally and cancels its emissions allowances formerly used for the generation of c-electricity. Then the pertaining comparative-static effects are as presented in Table 6.

		$\mathrm{d}y_{gA}^s$	$\mathrm{d}y_A^d$	$\mathrm{d}r_{xA}$	$\mathrm{d}p_y$	$\mathrm{d}q$	$\mathrm{d}x_A^s$	$\mathrm{d}x_A^d$
$\mathrm{d}\bar{y}_{cA}^s < 0$		$+$	$-$	$-$	$+$	$+$	$-$	?
	$\mathrm{d}y_{cB}^s$	$\mathrm{d}y_{gB}^s$	$\mathrm{d}y_B^d$	$\mathrm{d}r_{xB}$	$\mathrm{d}p_y$	$\mathrm{d}q$	$\mathrm{d}x_B^s$	$\mathrm{d}x_B^d$
$\mathrm{d}\bar{y}_{cA}^s < 0$	$-$	$+$	$-$	$-$	$+$	$+$	$-$	?

Table 6: Allocative impact of Scenario 3b

In order to understand the allocative displacement effects on the markets for permits and electricity listed in Table 6 suppose country A has phased out the generation of c-electricity, the emissions cap is reduced by the amount $\Delta\bar{e} = E^c(y_{c0}^s)$, and the initial equilibrium prices (p_{y0}, q_0) remain unchanged. Then the international electricity market is in excess demand, $y_{c0}^s + 2y_{g0}^s < 2y_0^d$, and the permit market is in equilibrium, $E^c(y_{c0}^s) + 2E^g(y_{g0}^s) = \bar{e}_1$.[10]

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[10]Recall that $\bar{e}_1 \equiv \bar{e}_0 - E^c(\bar{y}_{c0}^s)$.

The only way to remove the disequilibrium on the electricity market without creating a disequilibrium on the permit market is to combine an increase of the electricity price with an increase of the permit price. In the new joint equilibrium of the markets for permits and electricity the prices p_y and q are larger than in the initial equilibrium.

The common feature of the Scenarios 3b (Proposition 5) and 2b (Proposition 3) is that the pertaining comparative statics do not yield a clear sign for the change of the countries' consumption welfare. The ambiguity in Scenario 3b is less expected than in Scenario 2b because the emissions cap is smaller in 3b than in 2b. The smaller cap reduces the capacity of producing final goods in the two-country economy. In Scenario 2b the prices of electricity and permits are smaller and in Scenario 3b they are higher than in the absence of A's phase-out policy, and the production of final goods increases in Scenario 2b but decreases in 3b. Comparing the comparative statics of the Scenarios 3a and 3b reveals that both countries' consumption welfare decreases in Scenario 3a (Proposition 4) but not necessarily in Scenario 3b (Proposition 5), although no endogenous variable other than consumption welfare is unclear in sign or has different signs in the 3a and 3b.

4   Empirical calibration

In this section we empirically calibrate the two-country model to the European Union (EU-28) in the year 2018 and calculate the outcome for the unilateral phase-out policy when electricity markets are national or international. A and B are now two groups. Group A consists of the countries Germany, Italy, Netherlands, France and group B consists of the rest of EU 28.

As Table 7 shows, we selected the countries such that they form two groups with a fossil-fuel based electricity sector of (almost) equal size. This (approximate) symmetry yields an almost symmetric equilibrium of the markets for permits and electricity before coal is phased out - as in the analytical two-country model of the previous sections.[11] The specific emissions intensities are according to IPCC (2011, p. 10) $0.46 \frac{\text{t } CO_2}{\text{kWh}}$ and $1 \frac{\text{t } CO_2}{\text{kWh}}$ which yield $600 \, \text{M t}$ and $276 \, \text{M t}$ CO_2 emissions from coal and gas power plants, respectively, in 2018. The cost functions and emissions intensities are calibrated to a permit price of $20 \frac{\text{\euro}}{\text{t } CO_2}$ and to an electricity price of $p_y = 50 \frac{\text{\euro}}{\text{MWh}}$ at current coal and gas generation (see Table 7). We assume that the efficiency of coal power plants ranges from $35\,\%$ to $45\,\%$ with an average

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[11]The calibrated model deviates from the analytical model in that the initial consumption welfares differ across groups in the former but are equal across countries in the latter.

	gas in TWh	coal in TWh	$\sum$
Germany	84	229	
Italy	130	27	
Netherlands	55	34	
France	29	7	
group A	298	297	595
group B	316	327	663
EU-28	614	624	1238

Table 7: Electricity generation in 2018 (data from Agora Energiewende and Sandbag 2018)

of 40% and that the efficiency of gas plants ranges from 43% to 60% with an average of 51.5% (de Groot et al 2018). The gas price is $21\frac{\text{€}}{\text{MWh}}$ and the average of the lignite and hard coal price is $6\frac{\text{€}}{\text{MWh}}$ (see Fraunhofer 2018).

The resulting marginal cost and marginal emissions curves are displayed in Figure 5. The marginal emissions curves in Figure 5b deserve special attention, because the results in the comparative static analysis of the previous section rely on assumption (14) which requires that $y_0^s < \tilde{y}$, with $\tilde{y}$ being defined by $E_y^c(0) = E_y^g(\tilde{y})$. According to the first line of the Table 8 both countries' initial total generation of electricity is $y_0^s = 600\text{TWh}$. Inspection of Figure 5b readily yields $y_0^s = 600 < \tilde{y}$ and hence $E_y^c(0) > E_y^g(600)$ such that (14) holds for the calibrated model.
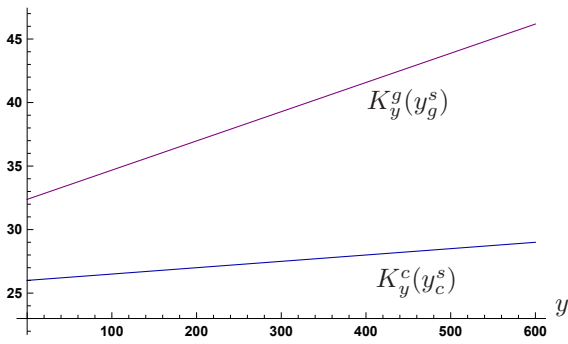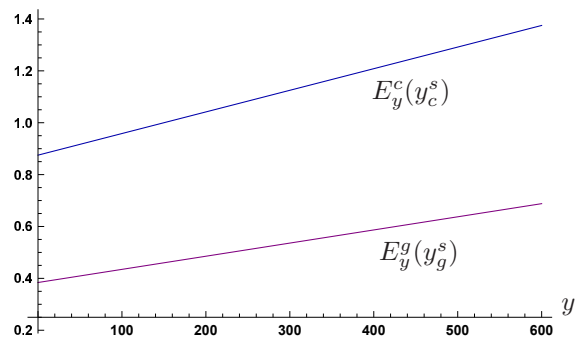

Figure 5a

Figure 5b

Figure 5: Calibrated marginal costs and emissions of coal and gas

	y_{cA}^s [TWh]	y_{gA}^s [TWh]	y_A^d [TWh]	y_{cB}^s [TWh]	y_{gB}^s [TWh]	y_B^d [TWh]	p_{yA} p_{yB} $\left[\frac{€}{\text{MWh}}\right]$	q $\left[\frac{€}{\text{t CO}_2}\right]$
baseline	300	300	600	300	300	600	50	20
national	0	515	515	458	273	731	53.33 46.03	13.66
international	0	354	603	499	354	603	49.87	16.56

Table 8: Equilibria on the markets for electricity and permits without and with the phase-out policies in the Scenarios 2a and 2b

The goods production is represented by the Cobb-Douglas production function

$$X(y, r_x) = y^\delta r_x^{\mu-\delta}, \tag{17}$$

where μ is the degree of homogeneity and δ is the energy income share. Following Hassler et al. (2018) we set $\delta = 0.055$. An empirical estimation of returns to scale is given by Gao and Kehrig (2017). They find $\mu = 0.96$ on average. Finally, the two-country economy is calibrated such that the groups' welfare levels equal the 2017 gross domestic product levels (GDP) $\hat{u}_A = 8031.047 \cdot 10^9$ € and $\hat{u}_B = 7346.324 \cdot 10^9$ €.

Table 8 displays the allocation on the markets for electricity and permits without and with group A's unilateral phase-out policy when electricity is either not traded or traded among the groups A and B. The first line presents the symmetric equilibrium before the phase-out. The allocation attained after group A's phase-out policy in the case of *national* electricity markets is listed in the second line of Table 8. The allocative displacement effects of that policy can be readily derived from comparing the first and second line of Table 8. As they should, the minus or plus signs of these effects coincide with those in Table 2, but Table 8 provides interesting additional information on orders of magnitude, of course. Interestingly, the relative decrease of the permit price is larger than the relative changes in electricity prices, and surprisingly, group A replaces the major part of its former generation of c-electricity by g-electricity, whereas group B combines the expansion of its total electricity generation with a massive increase of the share of c-electricity.[12] Hence, although group A phased out 300 TWh of c-electricity, the net reduction of c-electricity is only 142 TWh, because group B increased its generation of c-electricity by 158 TWh.

The allocation on the permit market and the *international* electricity market after group A phased out the generation of c-electricity is displayed in the third line of Table 8.

[12]Recall from Appendix A that if $dy_c^s + dy_g^s > 0$, then $dy_c^s > dy_g^s$.

	x_A^d	x_B^d
	$[10^9\,\text{€}]$	$[10^9\,\text{€}]$
baseline	8031.1	7346.3
national	8023.7	7349.4
international	8024.3	7350.8

Table 9: Welfare levels without and with the phase-out policies in the Scenarios 2a and 2b

The differences between the allocations attained when electricity is traded or not traded are remarkable. To begin with, the electricity price hardly declines when the electricity market is international such that each group's total electricity generation is (almost) unchanged. Both groups raise their generation of g-electricity by the same amount, but group B's increase of c-electricity is about twice as high. Therefore, the net reduction of c-electricity is only 146 TWh when the electricity market is international, which is even less than in case of national electricity markets. Since group B now exports 249 TWh electricity to group A it follows that group A phases out the amount of 300 TWh c-electricity but 'buys back' via imports 199 TWh of c-electricity and imports additional 50 TWh g-electricity from group B. Comparing the electricity prices of national electricity markets with the electricity price of the international market it is obvious that the deviations of electricity prices from the initial level is smaller in case of international electricity trade than in case of national electricity markets. This suggests that production distortions are larger in national than in international electricity markets

Table 9 displays the welfare effects of country A's unilateral phase-out policy. If electricity markets are national, that policy reduces country A's welfare by 7.4 billion € and it increases country B's welfare by 3.1 billion €. These are rather small shares of final goods consumption, but it is worth reemphasizing that country B benefits from country A's action and that country A's loss is significantly larger than country B's gains. In case of cross-border trade of electricity, the welfare changes are only slightly different. Country A suffers a welfare loss of 6.8 billion € whereas country B's welfare increases by 4.5 billion €. Thus, the simulation produces the clear result that country A suffers a welfare loss while country B is better off - as in the economy with national markets (Table 2). That result is remarkable because we have not been able to obtain a clear sign for the welfare changes in Table 3 in the economy with an international electricity market. Country A's partial positive terms-of-trade effect we identified in the comparative static analysis in the last section (and

	y_{cA}^s [TWh]	y_{gA}^s [TWh]	y_A^d [TWh]	y_{cB}^s [TWh]	y_{gB}^s [TWh]	y_B^d [TWh]	p_{yA} p_{yB} $\left[\frac{\text{€}}{\text{MWh}}\right]$	q $\left[\frac{\text{€}}{\text{t CO}_2}\right]$
baseline	300	300	600	300	300	600	50	20
tightened cap	148	320	468	148	320	468	55.47	28.78
national	0	439	439	222	311	533	57.03 52.55	24.01
international	0	354	477	246	354	477	55.06	25.77

Table 10: Equilibria on the markets for electricity and permits without and with the phase-out policies in the Scenarios 3a and 3b

which was the reason for the ambiguous sign in Table 3) turns out to be very small in our simulation. It is hardly conceivable that this small positive effect could ever overcompensate the other strong negative welfare effects. It is worth mentioning that the transition from national electricity markets to an international electricity market increases both countries' welfares due to gains from trade.

Table 10 shows the allocation of country A's unilateral phase-out policy in the Scenarios 3a and 3b. We have decomposed the phase-out policy into two steps. In the first step we have calculated the symmetric equilibrium when the initial emissions cap has been reduced to $\bar{e} - E_y^c(300)$. In the second step country A phases out coal at constant emissions cap $\bar{e} - E_y^c(300)$. The equilibrium at the tightened cap $\bar{e} - E_y^c(300)$ is displayed in the second line of Table 10. The equilibrium at the tightened cap and unilateral phase-out is listed in the third and fourth line of Table 10 for national and international electricity markets, respectively. Tightening the emissions cap drastically reduces the generation of more emissions-intensive c-electricity and slightly increases the generation of g-electricity. As expected, total electricity generation is driven back to reach the tighter emissions cap. Next, country A phases out coal. The displacement effects of the second step are similar to those explained in the context of Table 8.

Finally, we consider the welfare effects in Scenarios 3a and 3b. Table 11 reveals that both countries suffer a welfare loss from tightening the emissions cap. Country A has an additional welfare loss from phasing out. In contrast, the free-riding country B gains welfare from A's phase out. That welfare gain overcompensates the welfare loss due to the tightened cap. In sum, country A loses and country B gains welfare in Scenarios 3a

	x_A^d [10^9 €]	x_B^d [10^9 €]
baseline	8031.1	7346.3
tightened cap	8027.3	7342.6
national	8023.6	7344.5
international	8023.3	7345.6

Table 11: Welfare levels without and with the phase-out policies in the Scenarios 3a and 3b

and 3b. It is interesting to observe that these results hold irrespective of whether the electricity markets are national or international. However, opening borders for electricity trade increases aggregate welfare.

5 Concluding remarks

We consider a group of countries, such as the EU, with a joint ETS covering all installations generating electricity by means of natural gas or coal. The ETS countries commit to national emissions reduction goals and may apply the policy of phasing out their generation of coal-based electricity to reach these goals. Joint or national phase-out policies necessarily interfere with the ETS, since all coal-fired power plants are covered by the ETS. The paper analyzes the interaction of the ETS with such phase-out policies and specifies the resulting displacement effects, inefficiencies and welfare effects. The welfare effects are particularly striking. If all ETS countries phase out the generation of coal-based electricity while the emissions cap remains unchanged, all of them suffer a welfare loss. An individual country's unilateral phase-out policy makes that country worse off and the other countries better off. That result challenges common sense, which suggests that phasing out the dirtiest technology of generating electricity is the right thing to do when climate change mitigation is at issue. Even worse, unilateral action enhances the welfare of inactive 'free-riding' countries, and all these effects are generated without any contribution to mitigate climate change.

The basic economic rationale for the inefficiency created by the interference of phase-out policies with an ETS is straightforward. The raison d'être of an ETS is the uniform emissions price that secures cost-effectiveness by equalizing the marginal abatement costs of all firms covered by the ETS. The phase-out policy that implies divergent (shadow) permit prices. Put differently, the interference of the phase-out policy with an ETS is equivalent to applying a tax regime of differentiated tax rates on emissions from coal-based and gas-based

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electricity. The cost-effectiveness is violated even if there is no waterbed effect of emissions - as in the case of countries that are symmetric and phase out coal jointly. The upshot is that phasing out the generation of coal-based electricity via regulation perverts the concept of an ETS by eliminating the unique advantage an ETS is designed to offer, namely cost-effective abatement induced by a uniform carbon price. Although the allocative are quite differently if electricity markets are national or international, in our empirical calibration the welfare effects are qualitatively similar. The phasing-out country loses consumption welfare whereas the other free-riding countries gain consumption welfare. That holds irrespective of whether electricity markets are national or international, and irrespective of whether the emissions cap is constant or emissions allowances are cancelled. Opening the borders for trade in electricity increases the aggregate welfare due to gains from trade.

The contribution of the paper is a conceptual and rigorous analysis in a model that is simple enough to yield sharp results and has enough structure to map some features of the energy and climate policies in the EU that are relevant for the issue at hand. Although the reduction of complexity comes with the benefit of transparency and a clear focus on essentials, we are aware that the analytical framework contains various crude simplifications for reasons of tractability. The insights our analysis offers are limited, in particular due to our disregard of electricity generated by means of renewable energy resources and of important intertemporal features such as climate-friendly technical change, the tightening of the emissions cap over time, and borrowing and banking of permits. The integration of these items into the analysis of the interaction of an ETS with phase-out policies deserves high priority on the agenda of future research.

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Appendix A: Derivations

Derivation of (8): Total differentiation of (7) yields

$$X_{ry}\mathrm{d}y_i^d + X_{rr}\mathrm{d}r_{xi} = 0, \tag{A1}$$

$$X_{yy}\mathrm{d}y_i^d + X_{yr}\mathrm{d}r_{xi} = \mathrm{d}p_y, \tag{A2}$$

From (A1) and (A2) it follows

$$D_{p_y} \equiv \frac{\mathrm{d}y_i^d}{\mathrm{d}p_y} = \frac{X_{rr}}{X_{yy}X_{rr} - X_{ry}^2} < 0, \tag{A3}$$

$$R_{p_y} \equiv \frac{\mathrm{d}r_{xi}}{\mathrm{d}p_y} = -\frac{X_{ry}}{X_{yy}X_{rr} - X_{ry}^2} < 0. \tag{A4}$$

Derivation of (10): Differentiating (9) we obtain

$$\mathrm{d}p_y - (K_{yy}^h + qE_{yy}^h)\mathrm{d}y_{hi}^s - E_y^h\mathrm{d}q. \tag{A5}$$

From (A5) we infer

$$S_{p_y}^h \equiv \frac{\mathrm{d}y_{hi}^s}{\mathrm{d}p_y} = \frac{1}{K_{yy}^h + qE_{yy}^h} > 0, \quad S_q^h \equiv \frac{\mathrm{d}y_{hi}^s}{\mathrm{d}q} = -\frac{E_y^h}{K_{yy}^h + qE_{yy}^h} < 0. \tag{A6}$$

Derivation of $\frac{dp_y}{d\bar{e}} < 0$:   Consider the symmetric equilibrium[13]

$$x^s = X(y^d, r_x), \tag{A7}$$

$$p_y = qE^g_{y_i} + K^g_{y_i} \quad i = A, B, \tag{A8}$$

$$y^d = \bar{y}^s_c + y^s_g, \tag{A9}$$

$$\bar{e} = 2E^g(y^s_g) + 2E^c(y^s_c), \tag{A10}$$

$$X_r(r_x, y^d) = \bar{p}_r, \tag{A11}$$

$$X_y(r_x, y^d) = p_y, \tag{A12}$$

$$x^d = X(y^d, r_x) + \bar{p}_r(\bar{r} - r_x) - K^c(y^s_c) - K^g(y^s_g). \tag{A13}$$

Total differentiation of (A8)-(A12) leads to

$$dp_y = E^g_y dq + (K^g_{yy} + E^g_{yy})dy^s_g, \tag{A14}$$

$$dp_y = E^c_y dq + (K^c_{yy} + E^c_{yy})dy^s_c, \tag{A15}$$

$$dy^s_c + dy^s_g = dy^d, \tag{A16}$$

$$2E^g_y dy^s_g + 2E^c_y dy^s_c = d\bar{e}, \tag{A17}$$

$$X_{rr}dr_x + X_{ry}dy^d = 0, \tag{A18}$$

$$X_{yr}dr_x + X_{yy}dy^d = dp_y. \tag{A19}$$

In the sequel, we define $\tilde{K}^h_{yy} := K^h_{yy} + E^h_{yy}$ for $h = c, g$. Making use of $dr_x = -\frac{X_{ry}}{X_{rr}}dy^s$ from (A18) in (A19) we get

$$\left(\frac{X_{rr}X_{yy} - X^2_{ry}}{X_{rr}}\right) dy^d = -\alpha dy^d = dp_y, \tag{A20}$$

where $\alpha := -\frac{X_{rr}X_{yy} - X^2_{ry}}{X_{rr}} > 0$. Next, we insert

$$dy^s_c = \frac{d\bar{e}}{2E^c_y} - \frac{E^c_y}{E^g_y}dy^s_g \tag{A21}$$

from (A17) in (A16) to obtain

$$dy^d = \frac{d\bar{e}}{2E^c_y} + \left(\frac{E^c_y - E^g_y}{E^c_y}\right) dy^s_g. \tag{A22}$$

Combining (A14) and (A15) results in

$$\frac{E^c_y - E^g_y}{E^c_y E^g_y}dp_y = \frac{\tilde{K}^g_{yy}}{E^g_y}dy^s_g - \frac{\tilde{K}^c_{yy}}{E^c_y}dy^s_c. \tag{A23}$$

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[13]Observe that $y^s_{ci} = y^s_c$, $y^s_{gi} = y^s_g$, $r_{xi} = r_x$, $y^d_i = y^d$ for $i = A, B$.

Taking advantage of (A21) in (A23) we obtain

$$\frac{E_y^c - E_y^g}{E_y^c(\tilde{K}_{yy}^c + \tilde{K}_{yy}^g)} dp_y + \frac{E^g \tilde{K}_{yy}^c}{2(E_y^c)^2(\tilde{K}_{yy}^c + \tilde{K}_{yy}^g)} d\bar{e} = dy_g^s. \tag{A24}$$

Finally, we insert (A24) in (A22) which in turn is inserted in (A20) to obtain

$$-\frac{1}{2E_y^c}\left[1 + \frac{(E_y^c - E_y^g)E_y^g \tilde{K}_{yy}^c}{(E_y^c)^2(\tilde{K}_{yy}^c + \tilde{K}_{yy}^g)}\right] d\bar{e} = \left[\frac{1}{\alpha} + \frac{(E_y^c - E_y^g)^2}{(E_y^c)^2(\tilde{K}_{yy}^c + \tilde{K}_{yy}^g)}\right] dp_y. \tag{A25}$$

From (A25) we infer

$$\frac{dp_y}{d\bar{e}} < 0. \tag{A26}$$

Proof of $dy_c^s > dy_g^s$. From (A14) and (A15) it follows that

$$dy_c^s \gtreqless dy_g^s \quad \Longleftrightarrow \quad \left(\frac{1}{\tilde{K}_{yy}^c} - \frac{1}{\tilde{K}_{yy}^g}\right) dp_y \gtreqless \left(\frac{E_y^c}{K_{yy}^c} - \frac{E_y^g}{\tilde{K}_{yy}^g}\right) dq$$

$$\Longleftrightarrow \quad \tilde{K}_{yy}^g - \tilde{K}_{yy}^c \lesseqgtr (E_y^c \tilde{K}_{yy}^g - E_y^g \tilde{K}_{yy}^c)\frac{dq}{dp_y}. \tag{A27}$$

We know that $dy_c^s + dy_g^s > 0$ (if $d\bar{e} > 0$). Combined with $dy_h^s = \frac{1}{\tilde{K}_{yy}^h}(dp_y - E_y^h dq)$ this inequality yields, after some rearrangement of terms,

$$dp_y > E_y^g \frac{\frac{E_y^c}{E_y^g}\tilde{K}_{yy}^g + \tilde{K}_{yy}^c}{\tilde{K}_{yy}^c + \tilde{K}_{yy}^g} dq \quad \text{and hence} \quad dp_y > E_y^g dq \quad \text{or} \quad \frac{dq}{dp_y} > \frac{1}{E_y^g}. \tag{A28}$$

Finally, we consider $\frac{dq}{dp_y} > \frac{1}{E_y^g}$ in $(E_y^c \tilde{K}_{yy}^g - E_y^g \tilde{K}_{yy}^c)\frac{dq}{dp_y}$ from (A27) and get

$$(E_y^c \tilde{K}_{yy}^g - E_y^g \tilde{K}_{yy}^c)\frac{dq}{dp_y} > \frac{E_y^c \tilde{K}_{yy}^g - E_y^g \tilde{K}_{yy}^c}{E_y^g} = \frac{E_y^c}{E_y^g}\tilde{K}_{yy}^g - \tilde{K}_{yy}^c > \tilde{K}_{yy}^g - \tilde{K}_{yy}^c. \tag{A29}$$

(A29) combined with (A27) proves that $dy_c^s > dy_g^s$.

Derivation of (14):

Lemma 1.

Consider the generation of electricity in a symmetric equilibrium with $y_0^s = y_c^s + y_g^s$.

(i) $\Delta E(y_c^s, y_0^s) := E^g(y_0^s) - E^g(y_0^s - y_c^s) - E^c(y_c^s) < 0$ *for all $y_c^s \in [0, y_0^s]$, if $y_0^s < \tilde{y}$, where $\tilde{y}$ is defined by the equality $E_y^c(0) = E_y^g(\tilde{y})$.*

(ii) *If the emissions function E^h is given by $E^h(y_h^s) = a_h y_h^s + b(y_h^s)^2$ for $h = c, g$, then $\Delta E(y_c^s, y_0^s) < 0$ for all $y_g^s \in [0, y_0^s]$ if $y_0^s < \frac{a_c - a_g}{2b}$.*

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Proof:

(i) Consider first the polar cases. If $y_c^s = 0$, then $\Delta E(y_c^s, y_0^s) = E^g(y_0^s) = 0$. If $y_c^s = y_0^s$, then $\Delta E(y_c^s, y_0^s) = E^g(y_0^s) - E^c(y_0^s) < 0$. Lemma 1(i) is proved if $\Delta E(y_c^s, y_0^s)$ is monotone decreasing in y_c^s on the interval $[0, y_0^s]$. Differentiation yields

$$\frac{\mathrm{d}\Delta E}{\mathrm{d}y_c^s} \gtreqless 0 \qquad \Longleftrightarrow \qquad E_y^g(y_c^s) - E_y^c(y_g^s) \gtreqless 0.$$

If $y_0^s < \tilde{y}$ then $(\mathrm{d}\Delta E / \mathrm{d}y_c^s) < 0$ holds for all $y_c^s \in [0, y_0^s]$, since if $E_y^c(0) > E_y^g(y_0^s)$, then $E_y^c(y_c^s) > E_y^g(y_0^s - y_c^s)$ for all $y_c^s \in [0, y_0^s]$.

(ii) Consideration of $E^h(y_h^s) = a_h y_h^s + b(y_h^s)^2$ in $E^g(y_0^s) - E^g(y_g^s) - E^c(y_c^s) \gtreqless 0$ yields

$$a_g y_0^s + b\, y_0^{s2} \gtreqless a_c b\, y_c^{s2} + a_g y_g^s + b\, y_g^{s2}$$
$$\Longleftrightarrow \qquad a_g(y_0^s - y_g^s) + b(y_0^{s2} - y_c^{s2} - y_g^{s2}) \gtreqless a_c y_c^s$$
$$\Longleftrightarrow \qquad a_g y_c^s + 2b\, y_c^s y_g^s \gtreqless a_c y_c^s \qquad \Longleftrightarrow \qquad y_g^s \gtreqless \frac{a_c - a_g}{2b}.$$

Appendix B: Joint phase-out of coal

Consider the symmetric equilibrium (A7)-(A13) and assume that $\bar{y}_{cA} = \bar{y}_{cB} \equiv \bar{y}_c$ is chosen by the government of country $i = A, B$. Then total differentiation of (A7)- (A13) leads to

$$\mathrm{d}x^s = X_y \mathrm{d}y^d + X_r \mathrm{d}r_x, \tag{B1}$$
$$\mathrm{d}p_y = E_y^g \mathrm{d}q + (K_{yy}^g + qE_{yy}^g)\mathrm{d}y_g^s, \tag{B2}$$
$$\mathrm{d}\bar{y}_c^s + \mathrm{d}y_g^s = \mathrm{d}y^d, \tag{B3}$$
$$2E_y^g \mathrm{d}y_g^s + 2E_y^c \mathrm{d}\bar{y}_c^s = 0, \tag{B4}$$
$$X_{rr} \mathrm{d}r_x + X_{ry} \mathrm{d}y^d = 0, \tag{B5}$$
$$X_{yr} \mathrm{d}r_x + X_{yy} \mathrm{d}y^d = \mathrm{d}p_y, \tag{B6}$$
$$X_y \mathrm{d}y^d + X_r \mathrm{d}r_x - \bar{p}_r \mathrm{d}r_x - K_y^c \mathrm{d}\bar{y}_c^s - K_y^g \mathrm{d}y_g^s = \mathrm{d}x^d. \tag{B7}$$

From (B4) we get

$$\mathrm{d}y_g^s = -\frac{E_y^c}{E_y^g}\mathrm{d}\bar{y}_c^s. \tag{B8}$$

Inserting (B8) in (B3) we obtain

$$\mathrm{d}y^d = \frac{E_y^g - E_y^c}{E_y^g}\mathrm{d}\bar{y}_c^s. \tag{B9}$$

Inserting (B9) in (B5) yields

$$\mathrm{d}r_x = -\frac{X_{ry}}{X_{rr}}\mathrm{d}y^d = -\frac{X_{ry}}{X_{rr}}\left(\frac{E_y^g - E_y^c}{E_y^g}\right)\mathrm{d}\bar{y}_c^s. \tag{B10}$$

Making use of (B9) and (B10) in (B6) we get

$$\frac{\alpha(E_y^c - E_y^g)}{E_y^g}\mathrm{d}y_c^s = \mathrm{d}p_y. \tag{B11}$$

Finally we consider the welfare change (B8). Expanding by $p_y\mathrm{d}y^d - p_y\mathrm{d}\bar{y}_c^s - p_y\mathrm{d}y_g^s = 0$ and making use of $X_r = \bar{p}_r$ and $X_y = p_y$ yields

$$\mathrm{d}x^d = (p_y - K_y^c)\mathrm{d}\bar{y}_c^s + (p_y - K_y^g)\mathrm{d}y_g^s. \tag{B12}$$

Accounting for (A8) and $p_y - K_y^c = E_y^c q + \tau_y$ (where $\tau_y > 0$ is the shadow price of capping coal-based electricity) we obtain

$$\frac{\mathrm{d}x^d}{\mathrm{d}\bar{y}_c^s} = q\left(E_y^c + E_y^g\frac{\mathrm{d}y_g^s}{\mathrm{d}\bar{y}_c^s}\right) + \tau_y. \tag{B13}$$

Taking advantage of (B8) establishes

$$\frac{\mathrm{d}x^d}{\mathrm{d}\bar{y}_c^s} = \tau_y > 0. \tag{B14}$$

The results are summarized in Proposition 1.

Appendix C: Unilateral phase-out of coal with national electricity markets and constant emissions

The associated equilibrium is characterized by the equations

$$
\begin{aligned}
x_i^s &= X(y_i^d, r_{x_i}) \quad i = A, B, & \text{(C1)}\\
p_{yi} &= E_{y_i}^g q + K_{y_i}^g \quad i = A, B, & \text{(C2)}\\
p_{yB} &= E_{y_B}^c q + K_{y_B}^c, & \text{(C3)}\\
y_i^d &= y_{ci}^s + y_{gi}^s \quad i = A, B, & \text{(C4)}\\
\bar{e} &= E^g(y_{gA}^s) + E^c(y_{cA}^s) + E^g(y_{gB}^s) + E^c(y_{cB}^s), & \text{(C5)}\\
X_r(r_{xi}, y_i^d) &= \bar{p}_r \quad i = A, B, & \text{(C6)}\\
X_y(r_{xi}, y_i^d) &= p_{yi} \quad i = A, B, & \text{(C7)}\\
x_i^d &= X(y_i^d, r_{xi}) + \bar{p}_{ri}(\bar{r} - r_{xi}) - K^c(y_{ci}^s) - K^g(y_{gi}^s) \quad i = A, B, & \text{(C8)}\\
y_{cA}^s &= \bar{y}_{cA}^s. & \text{(C9)}
\end{aligned}
$$

In the sequel, we assume[14] $K_{yy}^c = E_{yy}^c \equiv 0$ which implies $E_{y_A}^c = E_{y_B}^c \equiv E_y^c$. Total differentiation of (C1) - (C9) leads to

$$\mathrm{d}x_i^s = X_y \mathrm{d}y_i^d + X_r \mathrm{d}r_{xi} \quad i = A, B, \tag{C10}$$

$$\mathrm{d}p_{yi} = E_{y_i}^g \mathrm{d}q + \tilde{K}_{yy}^g \mathrm{d}y_{gi}^s \quad i = A, B, \tag{C11}$$

$$\mathrm{d}p_{yB} = E_y^c \mathrm{d}q, \tag{C12}$$

$$\mathrm{d}y_A^d = \mathrm{d}\bar{y}_{cA}^s + \mathrm{d}y_{gA}^s, \tag{C13}$$

$$\mathrm{d}y_B^d = \mathrm{d}y_{cB}^s + \mathrm{d}y_{gB}^s, \tag{C14}$$

$$0 = E_{y_A}^g \mathrm{d}y_{gA}^s + E_y^c \mathrm{d}\bar{y}_{cA}^s + E_y^c \mathrm{d}y_{cB}^s + E_{y_B}^g \mathrm{d}y_{gB}^s, \tag{C15}$$

$$X_{rr} \mathrm{d}r_{xi} + X_{ry} \mathrm{d}y_i^d = 0 \quad i = A, B, \tag{C16}$$

$$X_{yr} \mathrm{d}r_{xi} + X_{yy} \mathrm{d}y_i^d = \mathrm{d}p_{yi} \quad i = A, B, \tag{C17}$$

$$\mathrm{d}x_A^d = X_y \mathrm{d}y_A^d + X_r \mathrm{d}r_{xA} - \bar{p}_r \mathrm{d}r_{xA} - K_y^c \mathrm{d}\bar{y}_{cA}^s - K_{y_A}^g \mathrm{d}y_{gA}^s, \tag{C18}$$

$$\mathrm{d}x_B^d = X_y \mathrm{d}y_B^d + X_r \mathrm{d}r_{xB} - \bar{p}_r \mathrm{d}r_{xB} - K_y^c \mathrm{d}y_{cB}^s - K_{y_B}^g \mathrm{d}y_{gB}^s. \tag{C19}$$

Combing (C11), (C12) and (C15) yields

$$\mathrm{d}y_{gA}^s = \frac{E_y^c \mathrm{d}p_{yA} - E_{y_A}^g \mathrm{d}p_{yB}}{E_y^c \tilde{K}_{yy}^g}, \quad \mathrm{d}y_{gB}^s = \frac{(E_y^c - E_{y_B}^g) \mathrm{d}p_{yB}}{E_y^c \tilde{K}_{yy}^g}, \quad \mathrm{d}q = \frac{\mathrm{d}p_{yB}}{E_y^c}, \tag{C20}$$

$$\mathrm{d}y_{cB}^s = -\frac{E_y^c E_{y_A}^g \mathrm{d}p_{yA} - \left[(E_{y_A}^g)^2 - E_y^c E_{y_B}^g + (E_{y_B}^g)^2\right] \mathrm{d}p_{yB} + (E_y^c)^2 \tilde{K}_{yy}^g \mathrm{d}\bar{y}_{cA}^s}{(E_y^c)^2 \tilde{K}_{yy}^g}. \tag{C21}$$

Making use of (C16) in (C17) we obtain

$$-\alpha_i \mathrm{d}y_i^d = \mathrm{d}p_{yi} \quad i = A, B. \tag{C22}$$

Next, we insert (C21) in (C22) to get

$$\frac{\mathrm{d}p_{yA}}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{\alpha_A \tilde{K}_{yy}^g \left[\alpha_B[(E_y^c)^2 + (E_{y_A}^g)^2 + (E_{y_B}^g)^2 - E_y^c(E_{y_A}^g + 2E_{y_B}^g)] + (E_y^c)^2 \tilde{K}_{yy}^g)\right]}{Z}, \tag{C23}$$

$$\frac{\mathrm{d}p_{yB}}{\mathrm{d}\bar{y}_{cA}^s} = \frac{\alpha_B E_y^c \tilde{K}_{yy}^g \left[(E_y^c - E_{y_A}^g)\alpha_A + E_y^c \tilde{K}_{yy}^g\right]}{Z} > 0, \tag{C24}$$

where

$$Z := (E_y^c)^2(\alpha_A + \tilde{K}_{yy}^g)(\alpha_B + \tilde{K}_{yy}^g) - E_{y_B}^g \alpha_B(\alpha_A + \tilde{K}_{yy}^g)(2E_y^c - E_{y_B}^g) + (E_{y_A}^g)^2 \alpha_B \tilde{K}_{yy}^g$$

$$= (\alpha_A + \tilde{K}_{yy}^g)\alpha_B \left[(E_y^c)^2\left(1 + \frac{\tilde{K}_{yy}^g}{\alpha_B}\right) - 2E_y^c E_{y_B}^g + (E_{y_B}^g)^2 + (E_{y_A}^g)^2\frac{\tilde{K}_{yy}^g}{\alpha_A + \tilde{K}_{yy}^g}\right] > 0. \tag{C25}$$

---

[14]The results of Appendix C also hold as long as K_{yy}^c and K_{yy}^g are sufficiently small.

Observe that $E_y^c(y_c^s) > 2E_y^g(y_0^s - y_c^s)$ for all $y_c^s \in [0, y_0^s]$ is sufficient for $\frac{\mathrm{d}p_{yA}}{\mathrm{d}\bar{y}_{cA}^s} < 0$. Inserting (C23) and (C24) into (C20)-(C22) results in

$$\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{(E_y^c)^2\alpha_A(\alpha_B + \tilde{K}_{yy}^g) + E_y^c\alpha_B[\tilde{K}_{yy}^g E_{yA}^g - 2\alpha_A E_{yB}^g] + (E_{yB}^g)^2\alpha_A\alpha_B}{Z} < 0, \text{(C26)}$$

$$\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} = \frac{\alpha_B(E_y^c - E_{yB}^g)\left[(E_y^c - E_{yA}^g)\alpha_A + E_y^c\tilde{K}_{yy}^g\right]}{Z} > 0, \tag{C27}$$

$$\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{\left[(E_y^c - E_{yA}^g)\alpha_A + E_y^c\tilde{K}_{yy}^g\right]\left[(E_y^c - E_{yB}^g)\alpha_B + E_y^c\tilde{K}_{yy}^g\right]}{Z} < 0 \tag{C28}$$

and

$$E_{yB}^g\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_y^c\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} = -E_{yA}^g\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} - E_y^c \tag{C29}$$

$$= -\frac{\left[(E_y^c - E_{yA}^g)\alpha_A + E_y^c\tilde{K}_{yy}^g\right]\left[(E_y^c)^2(\alpha_B + \tilde{K}_{yy}^g) - 2E_y^c E_{yB}^g\alpha_B + (E_{yB}^g)^2\alpha_B\right]}{Z} < 0 \text{(C30)}$$

Finally, the consumption welfare changes are given by

$$\frac{\mathrm{d}x_A^d}{\mathrm{d}\bar{y}_{cA}^s} = q\underbrace{\left(E_y^c + E_{yA}^g\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s}\right)}_{+} + \tau_y > 0, \tag{C31}$$

$$\frac{\mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = q\left(E_y^c\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_{yB}^g\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s}\right) < 0, \tag{C32}$$

$$\frac{\mathrm{d}x_A^d + \mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = q\left[E_y^c\left(1 + \frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s}\right) + \left(E_{yA}^g\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_{yB}^g\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s}\right)\right] + \tau_y = \tau_y > 0. \text{(C33)}$$

The results are summarized in Proposition 2.

Appendix D: Unilateral phase-out of coal with international electricity markets and constant emissions

The associated equilibrium is characterized by the equations

$$x_i^s = X(y_i^d, r_{x_i}) \quad i = A, B, \tag{D1}$$

$$p_y = qE_{yi}^g + K_{yi}^g \quad i = A, B, \tag{D2}$$

$$p_y = qE_{yB}^c + K_{yB}^c, \tag{D3}$$

$$y_A^d + y_B^d = y_{cA}^s + y_{gA}^s + y_{cB}^s + y_{gB}^s, \tag{D4}$$

$$\bar{e} = E^g(y_{gA}^s) + E^c(y_{cA}^s) + E^g(y_{gB}^s) + E^c(y_{cB}^s), \tag{D5}$$

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$$X_r(r_{xi}, y_i^d) = \bar{p}_r \quad i = A, B, \tag{D6}$$

$$X_y(r_{xi}, y_i^d) = p_y \quad i = A, B, \tag{D7}$$

$$x_i^d = X(y_i^d, r_{xi}) + \bar{p}_{ri}(\bar{r} - r_{xi}) + p_y(y_{ci}^s + y_{gi}^s - y_i^d)$$
$$- K^c(y_{ci}^s) - K^g(y_{gi}^s) \quad i = A, B, \tag{D8}$$

$$y_{cA}^s = \bar{y}_{cA}^s. \tag{D9}$$

Observe that equilibria are characterized by $y_{gA}^s = y_{gB}^s$ and $E_{yA}^g = E_{yB}^g \equiv E_y^g$ which follows from (D2).

Inserting (D9) in (D1) - (D8) and total differentiation leads to

$$\mathrm{d}x_i^s = X_y \mathrm{d}y_i^d + X_r \mathrm{d}r_{xi} \quad i = A, B, \tag{D10}$$

$$\mathrm{d}p_y = E_y^g \mathrm{d}q + \tilde{K}_{yy}^g \mathrm{d}y_{gi}^s \quad i = A, B, \tag{D11}$$

$$\mathrm{d}p_y = E_{yB}^c \mathrm{d}q + \tilde{K}_{yy}^c \mathrm{d}y_{cB}^s, \tag{D12}$$

$$\mathrm{d}y_A^d + \mathrm{d}y_B^d = \mathrm{d}\bar{y}_{cA}^s + \mathrm{d}y_{gA}^s + \mathrm{d}y_{cB}^s + \mathrm{d}y_{gB}^s, \tag{D13}$$

$$0 = E_y^g \mathrm{d}y_{gA}^s + E_{yA}^c \mathrm{d}\bar{y}_{cA}^s + E_{yB}^c \mathrm{d}y_{cB}^s + E_y^g \mathrm{d}y_{gB}^s, \tag{D14}$$

$$X_{rr} \mathrm{d}r_{xi} + X_{ry} \mathrm{d}y_i^d = 0 \quad i = A, B, \tag{D15}$$

$$X_{yr} \mathrm{d}r_{xi} + X_{yy} \mathrm{d}y_i^d = \mathrm{d}p_y \quad i = A, B, \tag{D16}$$

$$\mathrm{d}x_A^d = X_y \mathrm{d}y_A^d + X_r \mathrm{d}r_{xA} - \bar{p}_r \mathrm{d}r_{xA} - K_y^c \mathrm{d}\bar{y}_{cA}^s - K_y^g \mathrm{d}y_{gA}^s + T^A, \tag{D17}$$

$$\mathrm{d}x_B^d = X_y \mathrm{d}y_B^d + X_r \mathrm{d}r_{xB} - \bar{p}_r \mathrm{d}r_{xB} - K_y^c \mathrm{d}y_{cB}^s - K_y^g \mathrm{d}y_{gB}^s + T^B, \tag{D18}$$

where $T^i := \mathrm{d}p_y(y_{ci}^s + y_{gi}^s - y_i^d) + p_y(\mathrm{d}y_{ci}^s + \mathrm{d}y_{gi}^s - \mathrm{d}y_i^d)$.

From (D11), (D12) and (D2) we infer

$$\mathrm{d}y_{gA}^s = \mathrm{d}y_{gB}^s, \tag{D19}$$

and

$$\mathrm{d}y_{cB}^s = -\frac{E_{yB}^c - E_y^g}{E_y^g \tilde{K}_{yy}^c} \mathrm{d}p_y + \frac{E_{yB}^c \tilde{K}_{yy}^g}{E_y^g \tilde{K}_{yy}^c} \mathrm{d}y_{gi}^s. \tag{D20}$$

Making use of (D20) in (D14) yields

$$\mathrm{d}y_{cB}^s = -\frac{E_{yA}^c}{E_{yB}^c} \mathrm{d}\bar{y}_{cA}^s - \frac{2E_y^g}{E_{yB}^c} \mathrm{d}y_{gi}^s. \tag{D21}$$

Next, we combine (D20) and (D21) to obtain

$$\mathrm{d}y_{gi}^s = \frac{E_{yB}^c - E_y^g}{E_y^g \tilde{K}_{yy}^c \phi} \mathrm{d}p_y - \frac{E_{yA}^c}{\phi E_{yB}^c} \mathrm{d}\bar{y}_{cA}^s. \tag{D22}$$

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where $\phi := \frac{2(E_y^g)^2 \tilde{K}_{yy}^c + (E_{yB}^c)^2 \tilde{K}_{yy}^g}{E_{yB}^c E_y^g \tilde{K}_{yy}^c} > 0$. Inserting (D19) and (D22) in (D13) implies

$$
\begin{aligned}
\mathrm{d}y_A^d + \mathrm{d}y_B^d &= \frac{E_{yB}^c - E_{yA}^c}{E_{yB}^c}\mathrm{d}\bar{y}_{cA}^s + \frac{2(E_{yB}^c - E_y^g)}{E_{yB}^c}\mathrm{d}y_{gi}^s \\
&= \frac{2(E_{yB}^c - E_y^g)^2}{E_{yB}^c E_y^g \tilde{K}_{yy}^c \phi}\mathrm{d}p_y + \underbrace{\left[\frac{E_{yB}^c - E_{yA}^c}{E_{yB}^c} - \frac{2(E_{yB}^c - E_y^g)E_{yA}^c}{(E_{yB}^c)^2 \phi}\right]}_{=:-\mu}\mathrm{d}\bar{y}_{cA}^s. \quad \text{(D23)}
\end{aligned}
$$

Inserting ϕ into μ we obtain after tedious rearrangements

$$
\mu > 0 \quad\Longleftrightarrow\quad E_{yB}^c \tilde{K}_{yy}^g(E_{yB}^c - E_{yA}^c) < 2E_y^g \tilde{K}_{yy}^c(E_{yA}^c - E_{yB}^g). \quad \text{(D24)}
$$

(D24) is satisfies if $\tilde{K}_{yy}^g$ is sufficiently small.

Making use of (D15) in (D16) yields

$$
-\alpha_i \mathrm{d}y_i^d = \mathrm{d}p_y, \quad \text{(D25)}
$$

where $\alpha_i := -\frac{X_{rr}(r_{xi}, y_i^d)X_{yy}(r_{xi}, y_i^d) - X_{ry}(r_{xi}, y_i^d)^2}{X_{rr}(r_{xi}, y_i^d)} > 0$. From (D25) it follows

$$
\alpha_A \mathrm{d}y_A^d = \alpha_B \mathrm{d}y_B^d = -\mathrm{d}p_y. \quad \text{(D26)}
$$

Taking advantage of (D26) in (D23) yields

$$
\left[\frac{2(E_{yB}^c - E_y^g)^2}{E_{yB}^c E_y^g \tilde{K}_{yy}^c \phi} + \frac{1}{\alpha_A} + \frac{1}{\alpha_B}\right]\mathrm{d}p_y = \mu \mathrm{d}\bar{y}_{cA}^s, \quad \text{(D27)}
$$

which implies

$$
\frac{\mathrm{d}p_y}{\mathrm{d}\bar{y}_{cA}^s} > 0. \quad \text{(D28)}
$$

In view of (D22) (D23), (D25) and (D28) it holds

$$
\frac{\mathrm{d}y_A^d}{\mathrm{d}\bar{y}_{cA}^s} < 0, \quad \frac{\mathrm{d}y_B^d}{\mathrm{d}\bar{y}_{cA}^s} < 0, \quad \frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} < 0, \quad \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} < 0, \quad \frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} < 0. \quad \text{(D29)}
$$

Making use of (D29) in (D15) yields

$$
\frac{\mathrm{d}r_{xA}}{\mathrm{d}\bar{y}_{cA}^s} < 0, \quad \frac{\mathrm{d}r_{xB}}{\mathrm{d}\bar{y}_{cA}^s} < 0. \quad \text{(D30)}
$$

Finally, we consider the welfare change (D18). Making use of $X_r = \bar{p}_r$ and $X_y = p_y$ yields

$$
\begin{aligned}
\mathrm{d}x_A^d &= (p_y - K_{yA}^c)\mathrm{d}\bar{y}_{cA}^s + (p_y - K_{yA}^g)\mathrm{d}y_{gA}^s + (y_{cA}^s + y_{gA}^s - y_A^d)\mathrm{d}p_y, \quad \text{(D31)} \\
\mathrm{d}x_B^d &= (p_y - K_{yB}^c)\mathrm{d}y_{cB}^s + (p_y - K_{yB}^g)\mathrm{d}y_{gB}^s + (y_{cB}^s + y_{gB}^s - y_B^d)\mathrm{d}p_y. \quad \text{(D32)}
\end{aligned}
$$

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Accounting for (D2) and (D3) in (D31) and (D32) we obtain

$$
\frac{\mathrm{d}x_A^d}{\mathrm{d}\bar{y}_{cA}^s} = \underbrace{q\left(E_{y_A}^c + E_y^g\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s}\right)}_{+} + \tau_y + \underbrace{(\bar{y}_{cA}^s + y_{gA}^s - y_A^d)\frac{\mathrm{d}p_y}{\mathrm{d}\bar{y}_{cA}^s}}_{-}, \tag{D33}
$$

$$
\frac{\mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = \underbrace{q\left(E_{y_B}^c\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_y^g\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s}\right)}_{-} + \underbrace{(y_{cB}^s + y_{gB}^s - y_B^d)\frac{\mathrm{d}p_y}{\mathrm{d}\bar{y}_{cA}^s}}_{+}, \tag{D34}
$$

$$
\frac{\mathrm{d}x_A^d + \mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = q\left[E_{y_A}^c + E_{y_B}^c\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_y^g\left(\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} + \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s}\right)\right] + \tau_y = \tau_y > 0. \tag{D35}
$$

From (D2) it follows $y_{gA}^s = y_{gB}^s$. Since country A phases out coal, it holds $y_{cB}^s > \bar{y}_{cA}^s$ and hence country A imports electricity $\bar{y}_{cA}^s + y_{gA}^s < y_A^d$. The results are summarized in Proposition 3.

Appendix E: Unilateral phase-out of coal with national electricity markets and cancelling emissions allowances

The equilibrium of the model is characterized by the equations (C1)-(C4), (C6)-(C9) and

$$
\bar{e} - E^c(y_{cA}^s) = E^g(y_{gA}^s) + E^c(y_{cA}^s) + E^g(y_{gB}^s) + E^c(y_{cB}^s), \tag{E1}
$$

Total differentiation of these equations yields (C10)-(C14), (C16)-(C19) and

$$
E_{y_A}^g \mathrm{d}y_{gA}^s + E_y^c \mathrm{d}y_{cB}^s + E_{y_B}^g y_{gB}^s = 0. \tag{E2}
$$

Solving (C11)-(C14), (E2), (C16) and (C17) we obtain

$$
\frac{\mathrm{d}p_{yA}}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{\alpha_A\tilde{K}_{yy}^g\left[(E_y^c)^2(\alpha_B + \tilde{K}_{yy}^g) - 2E_y^cE_{y_B}^g\alpha_B + [(E_{y_A}^g)^2 + (E_{y_B}^g]^2)\alpha_B\right]}{Z} < 0, \tag{E3}
$$

$$
\frac{\mathrm{d}p_{yB}}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{E_y^cE_{y_A}^g\tilde{K}_{yy}^g\alpha_A\alpha_B}{Z} < 0, \tag{E4}
$$

$$
\frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{\alpha_A\left[(E_y^c)^2(\alpha_B + \tilde{K}_{yy}^g) - 2E_y^cE_{y_B}^g\alpha_B + (E_{y_B}^g)^2\alpha_B\right]}{Z} < 0, \tag{E5}
$$

$$
\frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{(E_y^c - E_{y_B}^g)E_{y_B}^g\ \alpha_A\alpha_B}{Z} < 0, \tag{E6}
$$

$$
\frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} = -\frac{E_{y_A}^g\alpha_A\left[E_y^c(\alpha_B + \tilde{K}_{yy}^g) - E_{y_B}^g\alpha_B\right]}{Z} < 0 \tag{E7}
$$

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and

$$E_y^c \frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_{y_B}^g \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} = -E_{y_A}^g \frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s}$$

$$= \frac{E_{y_A}^g \alpha_A \left[(E_y^c)^2(\alpha_B + \tilde{K}_{yy}^g) - 2E_y^c E_{y_B}^g \alpha_B + (E_{y_B}^g)^2 \alpha_B \right]}{Z} > 0, \quad \text{(E8)}$$

$$E_y^c + E_{y_A}^g \frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} = \frac{\alpha_A \alpha_B \left(E_y^c - E_{y_B}^g \right)^3 + E_y^c \tilde{K}_{yy}^g \alpha_B \left(E_y^c - E_{y_B}^g \right)^2}{Z}$$

$$+ \frac{(E_y^c)^2 \tilde{K}_{yy}^g \left[E_y^c(\alpha_A + \tilde{K}_{yy}^g) - E_{y_A}^g \alpha_A \right] + E_y^c(E_{y_A}^g)^2 \tilde{K}_{yy}^g \alpha_B}{Z} > 0. \text{(E9)}$$

Finally, the consumption welfare changes are given by The welfare changes are given by

$$\frac{\mathrm{d}x_A^d}{\mathrm{d}\bar{y}_{cA}^s} = q \left(E_y^c + E_{y_A}^g \frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} \right) + \tau_y > 0, \tag{E10}$$

$$\frac{\mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = q \left(E_y^c \frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_{y_B}^g \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} \right) = -q E_{y_B}^g \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} > 0, \tag{E11}$$

$$\frac{\mathrm{d}x_A^d + \mathrm{d}x_B^d}{\mathrm{d}\bar{y}_{cA}^s} = q \left[E_y^c \left(1 + \frac{\mathrm{d}y_{cB}^s}{\mathrm{d}\bar{y}_{cA}^s} \right) + E_{y_A}^g \frac{\mathrm{d}y_{gA}^s}{\mathrm{d}\bar{y}_{cA}^s} + E_{y_B}^g \frac{\mathrm{d}y_{gB}^s}{\mathrm{d}\bar{y}_{cA}^s} \right] + \tau_y = q E_y^c + \tau_y > 0. \tag{E12}$$

The results are summarized in Proposition 4.

Appendix F: Unilateral phase-out of coal with international electricity markets and cancelling emissions allowances

The equilibrium of the model is characterized by (D1)-(D4), (D6)-(D9) and (E1), Total differentiation of these equations yields

$$\mathrm{d}x_i^s = X_y \mathrm{d}y_i^d + X_r \mathrm{d}r_{xi} \quad i = A, B, \tag{F1}$$

$$\mathrm{d}p_y = E_y^g \mathrm{d}q + \tilde{K}_{yy}^g \mathrm{d}y_{gi}^s \quad i = A, B, \tag{F2}$$

$$\mathrm{d}p_y = E_y^c \mathrm{d}q + \tilde{K}_{yy}^c \mathrm{d}y_{cB}^s, \tag{F3}$$

$$\mathrm{d}y_A^d + \mathrm{d}y_B^d = \mathrm{d}\bar{y}_{cA}^s + \mathrm{d}y_{gA}^s + \mathrm{d}y_{cB}^s + \mathrm{d}y_{gB}^s, \tag{F4}$$

$$E_{y_A}^c \mathrm{d}\bar{y}_{cA}^s = E_y^g \mathrm{d}y_{gA}^s + E_{y_A}^c \mathrm{d}\bar{y}_{cA}^s + E_{y_B}^c \mathrm{d}y_{cB}^s + E_y^g \mathrm{d}y_{gB}^s, \tag{F5}$$

$$X_{rr} \mathrm{d}r_{xi} + X_{ry} \mathrm{d}y_i^d = 0 \quad i = A, B, \tag{F6}$$

$$X_{yr} \mathrm{d}r_{xi} + X_{yy} \mathrm{d}y_i^d = \mathrm{d}p_y \quad i = A, B, \tag{F7}$$

$$\mathrm{d}x_A^d = X_y \mathrm{d}y_A^d + X_r \mathrm{d}r_{xA} - \bar{p}_r \mathrm{d}r_{xA} - K_y^c \mathrm{d}\bar{y}_{cA}^s - K_y^g \mathrm{d}y_{gA}^s + T^A, \tag{F8}$$

$$\mathrm{d}x_B^d = X_y \mathrm{d}y_B^d + X_r \mathrm{d}r_{xB} - \bar{p}_r \mathrm{d}r_{xB} - K_y^c \mathrm{d}y_{cB}^s - K_y^g \mathrm{d}y_{gB}^s + T^B, \tag{F9}$$

Using the same steps of rearrangement as in Appendix D we obtain

$$dy_{gA}^s \;=\; dy_{gB}^s, \tag{F10}$$

$$dy_{cB}^s \;=\; -\frac{2E_y^g}{E_{y_B}^c}dy_{gi}^s, \tag{F11}$$

$$dy_{gi}^s \;=\; \frac{E_{y_B}^c - E_y^g}{E_y^g \tilde{K}_{yy}^c \phi}dp_y, \tag{F12}$$

$$dy_A^d + dy_B^d \;=\; \frac{2(E_{y_B}^c - E_y^g)^2}{E_{y_B}^c E_y^g \tilde{K}_{yy}^c \phi}dp_y + d\bar{y}_{cA}^s, \tag{F13}$$

$$-\alpha_i dy_i^d \;=\; dp_y. \tag{F14}$$

Combing (F13) in (F14) we get

$$\left[\frac{2(E_{y_B}^c - E_y^g)^2}{E_{y_B}^c E_y^g \tilde{K}_{yy}^c \phi} + \frac{1}{\alpha_A} + \frac{1}{\alpha_B}\right]dp_y = -d\bar{y}_{cA}^s, \tag{F15}$$

which implies

$$\frac{dp_y}{d\bar{y}_{cA}^s} < 0. \tag{F16}$$

In view of (F10)-(F12) and (F14) we get

$$\frac{dy_A^d}{d\bar{y}_{cA}^s} > 0, \quad \frac{dy_B^d}{d\bar{y}_{cA}^s} > 0, \quad \frac{dy_{gA}^s}{d\bar{y}_{cA}^s} < 0, \quad \frac{dy_{gB}^s}{d\bar{y}_{cA}^s} < 0 \quad \frac{dy_{cB}^s}{d\bar{y}_{cA}^s} > 0. \tag{F17}$$

Making use of (F17) in (F6) yields

$$\frac{dr_{xA}}{d\bar{y}_{cA}^s} > 0, \quad \frac{dr_{xB}}{d\bar{y}_{cA}^s} > 0. \tag{F18}$$

The consumption welfare changes are given by

$$\frac{dx_A^d}{d\bar{y}_{cA}^s} \;=\; q\left(E_{yA}^c + E_y^g\frac{dy_{gA}^s}{d\bar{y}_{cA}^s}\right) + \underbrace{(\bar{y}_{cA}^s + y_{gA}^s - y_A^d)\frac{dp_y}{d\bar{y}_{cA}^s}}_{+} + \tau_y, \tag{F19}$$

$$\frac{dx_B^d}{d\bar{y}_{cA}^s} \;=\; q\left(E_{yB}^c\frac{dy_{cB}^s}{d\bar{y}_{cA}^s} + E_y^g\frac{dy_{gB}^s}{d\bar{y}_{cA}^s}\right) + (y_{cB}^s + y_{gB}^s - y_B^d)\frac{dp_y}{d\bar{y}_{cA}^s}$$

$$=\; \underbrace{-qE_y^g\frac{dy_{gA}^s}{d\bar{y}_{cA}^s}}_{+} + \underbrace{(y_{cB}^s + y_{gB}^s - y_B^d)\frac{dp_y}{d\bar{y}_{cA}^s}}_{-}, \tag{F20}$$

$$\frac{dx_A^d + dx_B^d}{d\bar{y}_{cA}^s} \;=\; q\left[E_{yA}^c + E_{yB}^c\frac{dy_{cB}^s}{d\bar{y}_{cA}^s} + E_y^g\left(\frac{dy_{gA}^s}{d\bar{y}_{cA}^s} + \frac{dy_{gB}^s}{d\bar{y}_{cA}^s}\right)\right] + \tau_y = qE_{yA}^c + \tau_y > 0. \tag{F21}$$

The results are summarized in Proposition 5.