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Abstract

Several European countries have decided to phase out coal power generation. Emissions from electricity generation are already regulated by the EU Emissions Trading System (ETS), and in some countries like Germany the phaseout of coal will be accompanied with cancellation of emissions allowances. In this paper we examine the consequences of phasing out coal, both for the broader economy, the electricity sector, and for CO₂ emissions. We show analytically how the welfare impacts for a phaseout region depend on i) whether and how allowances are canceled, ii) whether other countries join phaseout policies, and iii) terms-of-trade effects in the ETS market. Based on numerical simulations with a computable general equilibrium model for the European economy, we quantify the economic and environmental impacts of alternative phaseout scenarios, considering both unilateral and multilateral phaseout. We find that terms-of-trade effects in the ETS market play an important role for the welfare effects across EU member states. For Germany, coal phaseout combined with unilateral cancellation of allowances is found to be welfare-improving if the German citizens value emissions reductions at 65 Euro per ton or more.

JEL-Codes: D610, F180, H230, Q540.

Keywords: coal phaseout, emissions trading, electricity market.

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1. Introduction

In order to keep global warming well below two degrees Celsius, most of the global coal reserves have to be left in the ground (McGlade and Ekins, 2015). Coal is the most carbon-intensive fossil fuel, and is also the dominant energy carrier in the electricity sector, with a global market share of more than one third (BP, 2019). There are currently numerous initiatives throughout the world to phase out coal, especially in electricity generation.¹ A large majority of the EU member states have decided to phase out coal (Agora Energiewende and Sandbag, 2020). Switching away from coal power to other electricity technologies is often regarded as the cheapest abatement option of some size (Gillingham and Stock, 2018). Moreover, global investment banks and funds are increasingly excluding coal power and coal extraction from their portfolio reflecting concerns on global climate change.² On the other hand, accelerated phaseout of coal power comes with additional costs of stranded investment, which must be traded off against the environmental benefits of CO₂ reduction. The aim of this paper is to shed some light into the heated policy debate on the pros and cons of a premature phaseout of coal.

In the EU, Germany is by far the biggest coal power producer (BP, 2019). The country has a long tradition in domestic coal mining, too, justified by domestic energy security considerations (Storchmann, 2005; Herpich et al., 2018). While domestic hard coal extraction has meanwhile been phased out on economic grounds, lignite extraction and associated power production is still competitive, securing thousands of jobs in economically weak areas. In the beginning of 2019, the German government-appointed coal commission suggested to gradually phase out coal-fired power generation and lignite mining by 2038 (Kommission “Wachstum, Strukturwandel und Beschäftigung”, 2019).³ The German government accepted that plan and put forward a proposed legislation for the parliament in January 2020 (Szabo and Garside, 2020).

In this paper we investigate the consequences of phasing out coal power generation by EU countries. We consider unilateral phaseout as well as joint phaseout by a coalition of several EU countries, examining both economy-wide effects, changes in the electricity market, and impacts on CO₂ emissions.

CO₂ emissions from electricity generation are already regulated by the EU Emissions Trading System (ETS). Hence, a decision to accelerate the phaseout of coal can risk the waterbed effect, that is, emissions in other parts of Europe may increase, given that the overall cap on emissions is fixed (Böhringer and Rosendahl, 2010). If so, one may risk ending up with additional welfare costs without additional climate benefits. In fear of the waterbed effect, the German coal commission proposed to cancel allowances along with the phaseout of coal (Szabo and Garside, 2020). Such cancellations to mitigate the waterbed effect may also take place through the Market Stability Reserve (MSR) reducing the long-term cap in the EU ETS (Perino, 2018).

We first develop a theoretical model that captures the most important elements needed to analyze the effects of coal phaseout in the electricity sector. In particular, we show how domestic welfare

¹ https://en.wikipedia.org/wiki/Fossil_fuel_phase-out

² More than 100 financial institutions globally have announced restrictions on financing coal power or coal mines, including e.g. JPMorgan and Morgan Stanley (IEEFA, 2020). In 2016, the world's biggest sovereign wealth fund, Norway's Government Pension Fund Global, decided to divest from coal companies (NBIM, 2016).

³ Evans (2019) assesses the business-as-usual German coal power capacity in 2038 to be 17 GW, compared to 38 GW in 2019.

impacts of coal phaseout depend on i) whether and how allowances are canceled, ii) whether or not other countries phase out coal, and iii) terms-of-trade effects in the ETS market.

Next, we apply a computable general equilibrium (CGE) model for the EU economy featuring a bottom-up representation of the electricity generation with discrete power technologies. As Germany accounts for one third of EU's coal power generation (BP, 2019) and pushes for a premature coal phaseout, our numerical analysis focuses on a German coal phaseout. However, we also consider unilateral phaseout in other EU countries as well as the joint phaseout in various EU countries. The simulation results show that the economic welfare costs of phasing out coal power depend crucially on the market share of coal power in the electricity sector. Hence, Germany is much more affected than most other EU countries (except Poland which is even more coal-based than Germany in power generation), facing non-negligible costs. The numerical results suggest that most other EU countries are slightly worse off by German coal phaseout. Most EU members are net exporters of emissions allowances, and thus face terms-of-trade losses in the ETS market as the ETS price drops significantly along with German coal phaseout. If many EU countries phase out coal jointly, most of them are worse off than when acting alone. The main explanation is again terms-of-trade losses in the ETS market due to stronger price reduction. Further, when disregarding environmental benefits, cancellation of allowances increases Germany's welfare costs. Accounting for environmental benefits, we find that a coal phaseout *cum* cancellation is welfare-improving for Germany (compared to no phaseout) if the German citizens value emissions reductions at 65 Euro per ton or more. If allowances are instead cancelled via the MSR, the required price tag is much lower.

Only a few previous papers have investigated the economy-wide impacts of phasing out coal, and its interactions with an ETS. The closest work to ours is by Eichner and Pethig (2019a) but they don't consider welfare gains from reduced emissions; furthermore, they provide only very rough quantitative estimates based on a simplistic calibration of their stylized analytical model, whereas we complement our theoretical analysis with quantitative insights from a large-scale CGE model of the European economy calibrated to national input-output accounts and bilateral trade flows. Oei et al. (2020) examine the implications of German coal phaseout for different parts of the country, through soft-linking an energy system model with an input-output model and a regional macroeconomic model for Germany, concluding that a faster phaseout would lead to a quicker recovery for the most exposed regions. Somewhat related, Gerarden et al. (2020) apply a model of the US electricity market and examines the effects of a surcharge on coal mining, effectively increasing the costs of coal power production. They find that such a policy can be almost as effective as a downstream CO₂ price for electricity generation.

Our paper contributes to the literature on overlapping regulation in climate policy. Several studies have analyzed and discussed the waterbed effect, as mentioned above. For instance, Böhringer and Rosendahl (2010) show that supporting green electricity also benefits the most emission-intensive electricity such as coal power if an emissions trading system with a fixed emissions cap is already in place: subsidizing green electricity depresses the emission price which benefits more emission-intensive coal at the expense of less emission-intensive gas. This is consistent with empirical findings in Novan (2017), that is, in a situation with emissions trading for NO_x in the US, expansion of renewables increased (unregulated) emissions of SO₂. On the other hand, Lecuyer and Quirion (2013) argue that overlapping regulation can be justified when there is uncertainty whether the emissions cap will be binding, while Newbery et al. (2019) make a case for the UK carbon price floor that overlaps with the EU ETS (see also Antimiani et al., 2016). Goulder and Stavins (2012) consider

interactions between federal and state climate policy in the US, concluding that state effort in the presence of federal policy can be useful or counterproductive.⁴

There is also a strand of literature discussing coal phaseout from a political economy or policy science perspective. For instance, Vogt-Schilb and Hallegatte (2017) argue that to minimize social and economic disruptions, policymakers can supplement low carbon prices with complementary policies such as moratoriums on new coal power plants. Aklin and Urpelainen (2013) discuss how political competition can influence sustainable energy transition paths, pointing to e.g. government's political costs of going against the interests of the fossil fuel industry. Oei et al. (2019) discuss the German policies leading up to the recent coal phaseout decision, emphasizing the need to combine climate, energy, social, and structural policies. Rinscheid and Wüstenhagen (2019) conclude based on a large-scale survey that the average German voter prefers a faster phaseout than the German coal commission and government have proposed. Another relevant issue, discussed in e.g. Newbery et al. (2019), is whether *domestic* emissions reductions is a separate motivation.⁵ Ancillary benefits from reduced emissions of local and regional pollutants can also be an additional motivation (Šcasný et al., 2015).

In the next section, we set up a stylized analytical model and derive some theoretical results regarding coal phaseout. In Section 3 we present our CGE analysis of alternative coal phaseout scenarios in the EU. Section 4 concludes.

2. Theoretical analysis

2.1 Model description

Consider a model with three regions ($r = 1, 2, 3$), which have a joint emissions trading system (ETS) that covers the electricity sector and the industry sector. The ETS price is denoted p^Q .

The electricity sector in each region consists of three technologies j , coal (C), gas (G) and carbon-free (R). To simplify, we disregard trade in electricity (bilateral trade in electricity is included in the numerical model). Production of electricity (E) from technology j in region r is denoted $y_{r,j}^E$. We assume that CO₂ emissions from coal and gas power production is proportional to output, but with different emissions intensities σ_j : $q_{r,j}^E = \sigma_j y_{r,j}^E$. For each technology, the costs of electricity production are (in aggregate) a strictly convex function of output: $c_{r,j}^E = c_{r,j}^E(y_{r,j}^E)$, with $c_{r,j}^{E'} > 0$ and $c_{r,j}^{E''} > 0$. The profits of electricity producers in region r by technology j on competitive electricity markets are then given by:

$$(1) \quad \pi_{r,j}^E = p_r^E y_{r,j}^E - c_{r,j}^E(y_{r,j}^E) - p^Q q_{r,j}^E = (p_r^E - \sigma_j p^Q) y_{r,j}^E - c_{r,j}^E(y_{r,j}^E)$$

The first-order condition for electricity producers is (assuming interior solution):

$$(2) \quad p_r^E = c_{r,j}^{E'}(y_{r,j}^E) + \sigma_j p^Q$$

⁴ Other studies of overlapping climate regulation are, e.g., Fischer and Preonas (2010), Jarke and Perino (2017), and Eichner and Pethig (2019b).

⁵ Several countries have national climate plans with specific targets for domestic emissions. For instance, Germany's target for 2030 is to cut domestic greenhouse gas emissions by at least 55 percent compared to 1990 levels (BMUB, 2016).

The industry sector (l) in each region is trading with the rest of the world at an exogenous world market price p^l .⁶ Production and emissions of the industry sector in each region is denoted y_r^l and q_r^l , while the sector's use of electricity is denoted e_r^l . The costs of production excluding purchase of electricity and emissions quotas are an increasing function of output and a decreasing function of both electricity use and emissions:⁷ $c_r^l = c_r^l(y_r^l, e_r^l, q_r^l)$. The cost function is strictly convex in output, electricity use and emissions; the cross-derivatives are assumed to be negative,⁸ and $\partial^2 c / \partial k \partial k \cdot \partial^2 c / \partial l \partial l - 2 \partial^2 c / \partial k \partial l > 0$ for any pair of variables y , e and q (inserted for k and l). The profit for industry producers are:

$$(3) \quad \pi_r^l = p^l y_r^l - c_r^l(y_r^l, e_r^l, q_r^l) - p_r^E e_r^l - p_r^Q q_r^l$$

The first order conditions for industry sector producers are then (assuming interior solution):

$$(4) \quad p^l = \partial c_r^l(y_r^l, e_r^l, q_r^l) / \partial y_r^l$$

$$(5) \quad p_r^E = -\partial c_r^l(y_r^l, e_r^l, q_r^l) / \partial e_r^l$$

$$(6) \quad p_r^Q = -\partial c_r^l(y_r^l, e_r^l, q_r^l) / \partial q_r^l$$

Consumers (and other sectors) also use electricity, denoted e_r^C , and their gross consumer surplus in the electricity market is an increasing and strictly concave function of electricity consumption:

$u_r^C = u_r^C(e_r^C)$. Net consumer surplus is given by:⁹

$$(7) \quad \pi_r^C = u_r^C(e_r^C) - p_r^E e_r^C$$

The first order condition for consumers is then (assuming interior solution):

$$(8) \quad p_r^E = u_r^C'(e_r^C)$$

Equilibrium in the electricity market in each region and in the ETS market is given by:

$$(9) \quad \sum_j y_{r,j}^E = e_r^l + e_r^C$$

$$(10) \quad \sum_r \left(\sum_j q_{r,j}^E + q_r^l \right) = \bar{Q} = \sum_r \bar{Q}_r$$

⁶ Hence, we treat the industry market very differently from the electricity market. Although this surely is a simplification, it reflects that industry products are much more traded internationally than electricity, the main reason being that costs of electricity transportation are much higher. Even within the EU, where electricity in principle can be freely traded between member states, gross trade in electricity amounts to a modest share of total electricity consumption in most countries.

⁷ Emissions here refer to direct emissions at the industry plant, not indirect emissions from the use of electricity. The assumption of costs decreasing in emissions simply mean that it is costly to reduce emissions.

⁸ This implies that the marginal costs of production (excl. payments for electricity and emissions) increase if either electricity use or emissions decline, and that electricity use and emissions are complementary goods. Note that emissions are closely linked to the use of fossil fuels at the industry plant. Whether electricity and emissions (fossil fuels) are complements or substitutes in reality, will differ among plants.

⁹ Since the industry sector is trading at an exogenous world market price, there are no direct link between the industry sector and the consumer surplus. Hence, we can disregard other factors that affect consumers' utility.

where \bar{Q} is the exogenous emissions cap, and \bar{Q}_r is the exogenous number of allowances allocated to region r .¹⁰ Let \bar{Q}^{REF} refer to the initial emissions cap, i.e., before any coal phaseout decision.

We assume that the regions may have different views about the climate change problem, and hence value potential emissions reductions differently.¹¹ Region r 's valuation per ton emissions reductions is denoted τ_r . We can think of this as a regional price tag on emissions, which can have different motivations.¹² We assume that the price tag is independent of whether emissions reductions take place domestically or abroad.¹³

National welfare is then given by the sum of consumer surplus, producer surplus in electricity and industry sectors, government revenues from sales of allowances, and valuation of emissions reductions (if any):

$$\begin{aligned}
 W_r &= \pi_r^C + \sum_j \pi_{r,j}^E + \pi_r^I + p^Q \bar{Q}_r + \tau_r (\bar{Q}^{REF} - \bar{Q}) \\
 &= u_r^C(e_r^C) - p_r^E e_r^C + \sum_j [p_r^E y_{r,j}^E - c_{r,j}^E(y_{r,j}^E) - p^Q q_{r,j}^E] + p^I y_r^I \\
 (11) \quad &- c_r^I(y_r^I, e_r^I, q_r^I) - p_r^E e_r^I - p^Q q_r^I + p^Q \bar{Q}_r + \tau_r (\bar{Q}^{REF} - \bar{Q}) \\
 &= u_r^C(e_r^C) - \sum_j c_{r,j}^E(y_{r,j}^E) + p^I y_r^I - c_r^I(y_r^I, e_r^I, q_r^I) + p^Q \left(\bar{Q}_r - \sum_j q_{r,j}^E - q_r^I \right) + \tau_r (\bar{Q}^{REF} - \bar{Q})
 \end{aligned}$$

The first term in (11) (last line) is gross consumer surplus, the second term is costs of electricity production, the third and four terms together are profits from industry production, the fifth term is net trade surplus in the emissions allowance market, while the last term is the value of emissions reductions.

2.1 Effects of phasing out of coal power

No change in emissions cap

Assume now that region 1 decides to phase out coal power ("coal phaseout"). Initially, regions 2 and 3 do not (below we consider the case when also region 2 phases out coal). Moreover, initially the emissions cap is unchanged. We consider first marginal exogenous reductions in coal use ($dy_{1,C}^E < 0$), so that we can analyze mathematically the sign of direction for the other variables. Phasing out coal power can then be seen as a succession of marginal reductions in coal use.

¹⁰ In the EU ETS, a large part of allowances are given out for free to the industry sector. Introducing exogenous free allocation to the industry sector wouldn't change our results as long as the sum of free allocation and auctioned allowances for each region is unchanged. In the numerical model we distinguish between free allocation and auctioned allowances.

¹¹ We disregard emissions outside the ETS, and also emissions outside the three regions. Interactions between ETS and Non-ETS sectors are likely of second order in our analysis of coal phaseout, as is carbon leakage to other regions too (Böhringer et al., 2017).

¹² The price tag may be motivated by e.g. an assumed social cost of carbon (for the world or the region), or to an assumed global carbon price consistent with the two (or 1.5) degrees target, or to other externalities that are not fully internalized such as technology spillovers or local air pollution, or to set the example for a decarbonized economy, or simply political economy motives such as pressure from lobby groups.

¹³ If the price tag were higher for domestic reductions, e.g., due to a target for national emissions (Newbery et al., 2019; BMUB, 2016), the welfare benefits from unilateral coal phaseout would intuitively increase.

Table 1 shows the sign of direction for the most interesting variables. We refer to Appendix A for a detailed derivation of these signs – here we just point to some important findings. Coal phaseout in region 1 implies excess demand in the domestic electricity market, and excess supply in the quota market. The former leads to higher electricity price, and stimulates production of gas and renewable power in region 1, while at the same time reducing electricity use. Excess supply in the quota market leads to a lower quota price, which stimulates gas power production further and increases industry emissions in region 1. However, as electricity use decreases due to higher electricity price, we cannot rule out that industry emissions may go down.

We further notice that the effects in regions 2 and 3 are almost the mirror image of what happens in region 1. The only link between the regions is via the ETS and the quota price. In particular, coal power production and industry emissions increase in regions 2 and 3, while the effects on gas power is ambiguous (in the simulations they increase).

Table 1. Effects of phasing out coal in region 1. Unchanged emissions cap

	dp_r^E	dp^Q	$dy_{r,C}^E$	$dy_{r,G}^E$	$dy_{r,R}^E$	dq_r^I	$\sum_j q_{r,j}^E$	dQ_r
Region 1	+	-	-	+	+	?	-	-
Regions 2&3	-	-	+	?	-	+	+	+

Next, we consider the effects on welfare in region r by a marginal reduction in coal power production in region 1 ($dy_{1,C}^E < 0$). By differentiating (11) (and using first order and equilibrium conditions above) we get for region 1:

$$(12) \quad dW_1 = (c_{1,C}^E (y_{1,C}^E) + \sigma_C p^Q - p_1^E) (-dy_{1,C}^E) + dp^Q \left(\bar{Q}_1 - \sum_j q_{1,j}^E - q_1^I \right)$$

Initially, when coal power generation is marginally reduced, the first parenthesis is zero (cf. (2)). The last parenthesis is also zero if we consider three symmetric regions, in which case there would be no initial net trade in emissions.¹⁴ However, as we continue to reduce coal power generation, the first parenthesis becomes more and more negative (the electricity price increases while the marginal production costs of coal power decreases) and also the second parenthesis becomes negative (gradually higher net export of emissions allowances combined with reduced quota price). Hence, the welfare effect of reducing coal power production is negative for region 1. If region 1 is initially a net importer of emissions quotas ($Q_r > \bar{Q}_r$), the last term in (12) is initially positive, and a marginal reduction in coal power production enhances domestic welfare. However, as coal power production is further reduced, the first term again becomes negative, and may eventually dominate the last term (which may also turn negative at some point if the region turns from a net importer into a net exporter of emissions quotas). Still, we cannot rule out the possibility that phasing out coal totally is welfare enhancing for region 1 if the region is a net importer of quotas.

Returning to the symmetric case, we concluded that welfare effects for region 1 are negative. One reason for this is that the phaseout of coal does not reduce total emissions as long as the emissions cap is unchanged (we consider changes in the emissions cap below). Furthermore, phaseout of coal

¹⁴ By symmetric regions, we mean identical utility and cost functions (and equal \bar{Q}_r), so that emissions, consumption and production are equal across regions (and hence no initial trade). τ_r may still vary though.

means that the region must rely on more expensive electricity production than before. This reduces the net surplus in the electricity market in region 1 (the gains from lower quota price is of second order here).

For regions 2 and 3, the welfare change is as follows:

$$(13) \quad dW_r = dp^Q \left(\bar{Q}_r - \sum_j q_{r,j}^E - q_r^I \right) \quad r = 2, 3$$

In the symmetric case, the welfare of the two regions will gradually increase as region 1 is phasing out coal, due to a combination of lower quota price and gradually higher net import of quotas. If region 2 or 3 is initially a net exporter of quotas, the initial welfare effect is negative for this region.

We sum up these results in the following proposition:

Proposition 1.

Consider an ETS regulating emissions in several regions. If one region reduces its coal power generation unilaterally, then:

- *The welfare effects of this region are negative if it is not a net importer of quotas initially.*
- *For each of the other regions the welfare effects are positive if it is not a net exporter of quotas initially.*

Change in the emissions cap

So far, we have assumed that the emissions cap is unchanged. Inspired by more recent developments in the EU ETS, which open up for adjustments of the EU-wide cap, we will now consider two alternative ways the cap can be reduced alongside the coal phaseout. First, region 1 may decide to cancel allowances unilaterally by reducing its share of auctioned allowances:

$d\bar{Q}_1 = \omega^U \sigma_C dy_{1,C}^E < 0$, where ω^U is the unilateral cancellation rate where we assume $0 < \omega^U \leq 1$. If $\omega^U = 1$, the reduction of the cap corresponds exactly to the emissions from the reduced coal power production. Second, the cap may be automatically reduced as a response to reduced demand for allowances, with proportional reductions in all regions' auctioned allowances:

$d\bar{Q} = \omega^A (\sigma_C dy_{1,C}^E) < 0$ with $0 < \omega^A \leq 1$ and $d\bar{Q}_r = (\bar{Q}_r / \bar{Q}) d\bar{Q}$. This setting is mimicking the Market Stability Reserve (MSR) in the EU ETS within a static framework, and we will refer to this as joint cancellation.¹⁵

Whether the cap is reduced unilaterally or jointly has no bearing for the market outcome in our model, but it is important for the regional welfare assessment. The market effects for the three regions are now more ambiguous. First of all, it depends on the cancellation rate – if this is close to zero, we are basically back to the case in Table 1 with unambiguously lower quota price. If the cancellation rate is set to one, the quota price may decrease or increase. The outcome depends on how gas power production and industry activity in region 1 react to higher electricity price (cf. Appendix A). If higher emissions from gas power production dominate lower industry emissions *at the initial quota price*, the quota price will increase. If industry emissions respond strongest, the quota price will decrease. In the latter case (“Alternative 1”), i.e., if the quota price drops, we get the

¹⁵ As mentioned in the introduction, the MSR most likely implies that reduced demand for allowances in the near future will decrease the long-term emissions cap, while the implications are more uncertain if demand is reduced several years from now. We return to this issue in the numerical simulations.

same qualitative results as without any change in the emissions cap (see Table 1). However, the quantitative impacts are smaller. If the quota price increases ("Alternative 2"), the effects in regions 2 and 3 are turned around, see Table 2. Effects in region 1 are almost the same as before (qualitatively), except that industry emissions now unambiguously fall. The numerical simulations in Section 3 suggest that for most regions Alternative 2 is most likely if the cancellation rate is high, i.e., the quota price increases. An intuitive reason is that gas power generation is likely to respond more to electricity price changes than industry production, provided that gas power is a viable option in that region.

Table 2. Effects of phasing out coal in region 1 combined with cancellation of allowances.
Alternative 2: Higher quota price*

	dp_r^E	dp^Q	$dy_{r,C}^E$	$dy_{r,G}^E$	$dy_{r,R}^E$	dq_r^I	$\sum_j q_{r,j}^E$	dQ_r
Region 1	+	+	-	+	+	-	-	-
Regions 2&3	+	+	-	?	+	-	-	-

* Alternative 1 (lower quota price) has the same signs as in Table 1.

The welfare effects are slightly changed since total emissions are no longer fixed. In the case with unilateral cancellation, we get the following expressions for respectively region 1 and regions 2 and 3:

$$(14) \quad dW_1 = (c_{1,C}^E (y_{1,C}^E) + \sigma_C p^Q - p_1^E) (-dy_{1,C}^E) + dp^Q \left(\bar{Q}_1 - \sum_j q_{1,j}^E - q_1^I \right) + \omega^U \sigma_C (-dy_{1,C}^E) (\tau_1 - p^Q)$$

$$(15) \quad dW_r = dp^Q \left(\bar{Q}_r - \sum_j q_{r,j}^E - q_r^I \right) + \omega^U \tau_r \sigma_C (-dy_{1,C}^E) \quad r = 2, 3$$

Note that there is an additional term in both expressions, reflecting the cancellation of allowances and hence reduced overall emissions. If region 1 values emissions reductions at the initial quota price, $\tau_1 = p^Q$, this last term is initially zero and hence the welfare effect of a marginal reduction in coal power is still zero in the case with symmetric regions. Moreover, a further reduction of coal power production along with cancellation of allowances will reduce welfare, as the sum of the first and third term becomes more and more negative (irrespective of whether the quota price increases or decreases), and the second term is also negative.¹⁶ Hence, in this case the effects on welfare are qualitatively the same as without cancellation. If $\tau_1 < p^Q$, then this policy is obviously decreasing welfare, also initially.

On the other hand, if region 1 has a higher valuation of emissions than reflected by the initial quota price, meaning $\tau_1 > p^Q$, then a marginal reduction in coal power, combined with cancellation of allowances, enhances welfare initially (again assuming symmetric regions). However, as coal power production is reduced further, and eventually phased out, the welfare effect is generally ambiguous and depends crucially on the size of τ_1 (relative to p^Q), as well as the welfare costs of discarding profitable coal power generation. The size of the second term in (14) is still negative (see above), but most likely smaller in size than in (12), since the quota price changes less.

¹⁶ There will either be net export of allowances from region 1 and lower quota price (Alternative 1, see Table 1), or net import of allowances and higher quota price (Alternative 2, see Table 2).

If the regions are not symmetric, it also matters whether region 1 is initially a net importer or exporter of quotas. In the former case, a marginal reduction of coal power might be beneficial even if $\tau_1 < p^Q$, while in the latter case it might reduce welfare even if $\tau_1 > p^Q$.

The welfare impacts of gradually phasing out coal combined with unilateral cancellation of allowances can be illustrated in Figure 1. Four alternatives are shown, where three of them assume initial welfare gains (e.g., symmetric regions and $\tau_1 > p^Q$). In the “Initial loss” case, no reduction of coal power is obviously the best choice. In the “Low initial gains” case, reducing some coal generation would be beneficial, but phasing out all coal generation reduces welfare compared to the initial situation. In the “Medium initial gains” case, completely phasing out coal enhances welfare, but the optimal regulation is to only partly phase out coal, that is, reduce coal generation until the point where the curve intersects with the horizontal axis (i.e., where dW turns negative). Finally, in the “High initial gains” case, completely phasing out coal is in fact the optimal policy, as the welfare effects of an additional reduction in coal generation are always positive. Which of the four alternatives that apply is an empirical question and may vary across regions.

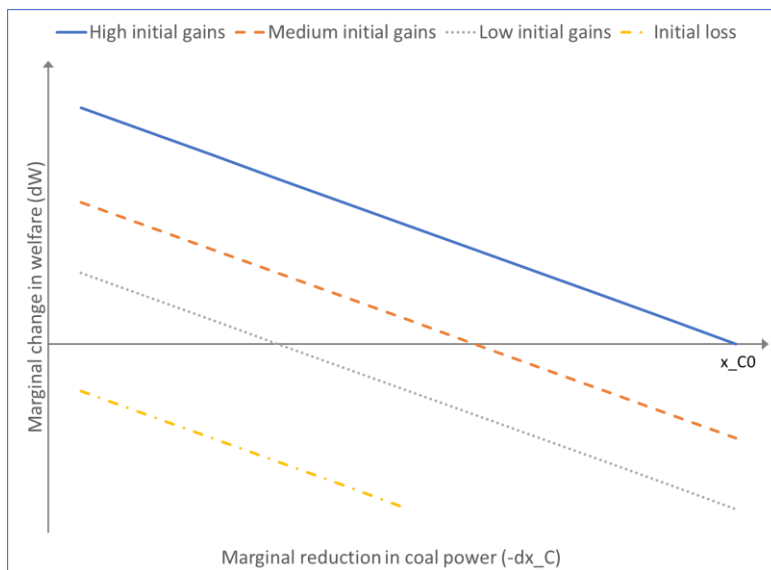


Figure 1. Marginal welfare effects in region 1 of gradually phasing out coal power production in region 1, combined with unilateral cancellation of allowances. Illustration of four different cases.

Regions 2 and 3 will still have higher welfare from coal phaseout in region 1, as their terms of trade in the ETS market still improves (in both Alternative 1 and 2). In addition, they get a positive effect from lower global emissions (last term in (15)). Hence, (partly) phasing out coal might be a win-win situation for the three regions if region 1 has a high valuation of emissions reductions.

So far, we have assessed the welfare implications of coal phaseout *without* cancellation, and of coal phaseout *with* cancellation, but what about the difference between these two? That is, what if region 1 has decided to phase out coal and considers whether to also cancel allowances. From the discussion above, we can unambiguously state the following in the symmetric case: If region 1 reduces its coal power production marginally from its initial level, it is better off by cancelling allowances if and only if $\tau_1 > p^Q$. When coal power production is reduced further, things become ambiguous. The last term in (14) will still be positive if and only if $\tau_1 > p^Q$, but the size of the two first terms in (12) and (14) will differ (since the variables will differ in size). However, the second

term will very likely be less negative with cancellation than without, as both the price decrease and net export in the ETS market will be lower (and possibly shift sign) with cancellation. That is, cancellation is good from a terms-of-trade perspective in the ETS market. The first term is more difficult to assess, as cancellation of quotas will increase both the quota price and the electricity price. To sum up, there is one ambiguous and one positive effect of cancellation (first and second terms in (14)) and one that is positive if and only if $\tau_1 > p^Q$. This jointly suggests that it is likely welfare enhancing to combine phasing out coal with cancellation of quota if the price tag on emissions is at least as high as the ETS price (this is the case in the simulations below). However, again this is an empirical question.

We sum up the main findings above in the following proposition:

Proposition 2.

Consider an ETS regulating emissions in several regions. If one region reduces its coal power generation unilaterally followed by unilateral cancellation of emissions allowances, then:

- *If the regions are symmetric, then the welfare effect for acting region of the first unit of coal power reduction is positive if and only if its valuation of emissions exceeds the ETS price.*
- *Whether a complete phaseout of coal is beneficial for the acting region, and whether coal phaseout with cancellation of allowances improves its welfare compared to coal phaseout without cancellation, are ambiguous and depend crucially on the region's emissions valuation.*
- *The welfare effects for each of the other regions are positive if it is not a net exporter of quotas initially.*

Assume now instead that the emissions cap is jointly reduced along with decreased demand for allowances, meaning that the reduced auctioning is distributed across regions instead of applying only to region 1. The welfare effects are then:

(16)

$$dW_1 = \left(c_{1,C}^E (y_{1,C}^E) + \sigma_C p^Q - p_1^E \right) (-dy_{1,C}^E) + dp^Q \left(\bar{Q}_1 - \sum_j q_{1,j}^E - q_1^I \right) + \omega^A \sigma_C (-dy_{1,C}^E) \left(\tau_1 - \frac{\bar{Q}_1}{Q} p^Q \right)$$

$$(17) \quad dW_r = dp^Q \left(\bar{Q}_r - \sum_j q_{r,j}^E - q_r^I \right) + \omega^A \sigma_C (-dy_{1,C}^E) \left(\tau_1 - \frac{\bar{Q}_r}{Q} p^Q \right) \quad r = 2, 3$$

The last term in (16) is more likely to be positive than the last term in (14), especially if region 1 is relatively small, as cancellation of allowances is distributed across regions. Thus, starting to phase out coal may be welfare-improving for region 1 even if $\tau_1 < p^Q$. On the other hand, if region 1 has a high valuation of emissions reductions, and $\omega^A \ll \omega^U$, the last term in (14) may be bigger than (16). Thus, it might be the case that a complete phaseout of coal is welfare-improving with unilateral cancellation of quotas but not with joint (but more limited) cancellation of quotas.

For regions 2 and 3 the welfare effects are now more ambiguous as they lose income from sales of allowances. If they have low valuation of emissions reductions, their welfare is likely reduced.

We sum up our findings in the following proposition:

Proposition 3.

Consider an ETS regulating emissions in several regions. If one region reduces its coal power generation unilaterally followed by joint cancellation of emissions allowances, then:

- The welfare effect for the acting region of the first unit of coal power reduction is positive if its valuation of emissions is not too far below the ETS price and it is not a net exporter of quotas.
- Whether a complete phaseout of coal is beneficial for the acting region, and whether coal phaseout with cancellation of allowances improves its welfare compared to coal phaseout without cancellation, are ambiguous and depend crucially on the region's valuation of emissions.
- The welfare effects for the other regions are ambiguous.

Joint phaseout of coal by several regions

What if region 2 goes together with region 1 in phasing out coal? In this subsection we assume symmetric regions. Obviously, for region 3 the welfare effects are positive as before, but stronger.

Without cancellation, the welfare effects for regions 1 and 2 are given by equation (12) (with subscript $r = 1, 2$ instead of 1). For region 2, the welfare effects correspond to what we found for region 1 above. That is, the marginal welfare effect is initially zero, but then more and more negative as more and more coal is phased out.

For region 1, it is ambiguous whether its welfare effects become more or less negative when region 2 joins. Both terms in (12) can go either up or down.¹⁷

With unilateral cancellation by the two regions (and equal ω^U), the welfare effects for regions 1 and 2 are given by a slightly modified equation (14):

$$(18) \quad \begin{aligned} dW_r = & \left(c_{r,C}^E (y_{r,C}^E) + \sigma_C p^Q - p_r^E \right) (-dy_{r,C}^E) + dp^Q \left(\bar{Q}_r - \sum_j q_{r,j}^E - q_r^I \right) \\ & + \omega^U \sigma_C \left(\left(\sum_{k=1}^2 -dy_{k,C}^E \right) \tau_r - (-dy_{r,C}^E) p^Q \right) \quad r = 1, 2 \end{aligned}$$

Now the marginal welfare impacts for the two regions are initially strictly positive if the regions value emissions reductions at $\tau_r = p^Q$. Hence, all three regions gain from this policy, which may seem surprising at first glance. The intuition is that the total welfare gain (for the three regions together) from one unit emissions reduction is $\sum_r \tau_r > p^Q$.¹⁸ Whether complete coal phaseout is

welfare improving or not is ambiguous as before. If $\tau_r < 0.5p^Q$, the welfare effect is negative also for the first unit of reduction.

For region 1 it is most likely beneficial that region 2 also phases out coal in the case with unilateral cancellation. For marginal reductions in coal power, it is unambiguously beneficial that region 2 joins, as the first two terms in (14) and (18) are zero, while the last term is biggest in (18). For bigger reductions it is slightly more ambiguous. However, we noticed above that the effect on the quota price of this policy is not clear. If the quota price doesn't change when region 2 joins in, the two first

¹⁷ In the first term, both the quota price and the electricity price decline. In the second term, the decline in the quota price becomes bigger whereas the net export becomes smaller.

¹⁸ This illustrates a potential inconsistency of summing the value of emissions reductions over several countries, especially if τ_r is set equal to the *global* social cost of carbon. It's beyond the scope of this paper to discuss what the appropriate value of τ_r should be. An alternative approach to (18) could be that each country only values the emissions reductions following from its own actions.

terms in (14) and (18) do not change, and hence region 1's welfare becomes unambiguously more positive or less negative.

With joint cancellation, the welfare effects for regions 1 and 2 become:

$$(19) \quad \begin{aligned} dW_1 = & \left(c_{1,C}^E (y_{1,C}^E) + \sigma_C p^Q - p_1^E \right) (-dy_{1,C}^E) + dp^Q \left(\bar{Q}_1 - \sum_j q_{1,j}^E - q_1^I \right) \\ & + \omega^A \sigma_C \left(\sum_{k=1}^2 -dy_{kC}^E \right) \left(\tau_1 - \frac{\bar{Q}_1}{Q} p^Q \right) \quad r = 1, 2 \end{aligned}$$

The only difference compared to (16) (when region 1 acts alone) is that the last term is bigger in absolute value. Hence, if a marginal reduction in coal power generation is beneficial for region 1, it is even more beneficial if region 2 also joins. However, region 1 benefits less from region 2's participation compared to unilateral cancellation as some of the additional cancellation means less sales of allowances from region 1.

Proposition 4.

Consider an ETS regulating emissions in several symmetric regions, and that one region has already decided to reduce its coal power generation. If a second region makes the same decision, then:

- *The impact on the first region's welfare is ambiguous if there is no cancellation of allowances, or if there is joint cancellation of allowances.*
- *If coal phaseout is combined with unilateral cancellation, the welfare effect for the first region (of the second region's decision) is positive if the impact on the quota price is sufficiently small.*

3. Numerical analysis

Our theoretical analysis provides valuable insights into the fundamental economic effects triggered by coal phaseout policies. Yet, it is stylized and misses various real-world features that are potentially important for drawing viable policy conclusions. For example, countries are heterogeneous in production and consumption and we typically observe electricity trade between neighboring countries. Furthermore, economic adjustments to a coal phaseout is driven through complex substitution, output and income effects across multiple markets triggered by policy-induced changes in relative prices. We therefore complement our theoretical partial equilibrium analysis with computable general equilibrium (CGE) simulations based on empirical data. The strength of CGE models is their rigorous microeconomic foundation in Walrasian equilibrium theory, which accommodates the comprehensive welfare analysis of market supply and demand responses to policy shocks. Quantitative equilibrium analysis provides counterfactual ex-ante comparisons, assessing the outcomes with a reform in place against a reference situation without such a reform. Below, we first provide a non-technical summary of the CGE model and its parameterization. We then lay out alternative policy scenarios of phasing out coal and discuss simulation results.

3.1 Model structure, data and parametrization

We adopt a standard multi-region multi-sector CGE model of global trade and energy use (see e.g. Böhringer et al. 2015, 2018), but refine the modeling of the electricity sector compared to a standard

CGE model. For the sake of brevity, we refer to Appendix B for a non-technical summary of key model characteristics,¹⁹ and center our attention here on how the electricity sector is modeled.

Given the paramount importance of the electricity sector with respect to the phaseout of coal, we distinguish different power generation technologies that produce electricity by combining inputs of labor, fuel, and materials with technology-specific resources (capital and natural resources such as water, sun, wind, biomass). For each technology, power generation takes place with decreasing returns to scale and responds to changes in electricity prices according to technology-specific supply elasticities (see Appendix B for details). Within each region, electricity output from different technologies is treated as a homogeneous good which enters as an input to the regional distribution and transmission electricity sector. Bilateral trade is modeled following Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington, 1969). Trade in electricity takes place only via the distribution and transmission electricity sector.²⁰

For model parameterization, base-year data together with exogenous elasticities determine the free parameters of the functional forms. We use most recent data from the global macroeconomic balances as published by the Joint Research Centre (JRC) of the EU Commission (Keramides et al. 2018, and Rey Los Santos et al., 2018). The JRC data includes detailed macroeconomic accounts on production, consumption, and bilateral trade together with information on physical energy flows and CO₂ emissions for 40 regions and 31 sectors covering the overall world economy.²¹ The electricity sector in the JRC dataset is decomposed by region into 11 discrete generation technologies and a residual transmission and distribution sector.

Beyond the explicit information on discrete power technologies, another appealing feature of the JRC dataset is that it includes official baseline projections of future economic activities and energy use in five-year intervals until 2050.²² We can readily use these projected input-output tables and bilateral trade flow for our model calibration thereby establishing a baseline scenario against which we measure the implications of policy counterfactuals such as alternative coal phaseout scenarios.

The JRC dataset can be flexibly aggregated across sectors and regions to reflect specific requirements of the policy issue under investigation. For our analysis, we keep with all the different primary and secondary energy carriers in the original dataset: Coal, Crude Oil, Natural Gas, Refined Oil, and Electricity. This disaggregation is essential in order to distinguish energy goods by CO₂ intensity and the degree of substitutability. In addition, we keep all emission-intensive and trade-exposed (EITE) industries covered by the EU ETS (i.e., Chemical Products, Non-Metallic Minerals, Iron & Steel, Non-Ferrous Metals, and Air Transport) separate. Furthermore, we maintain the detailed description of electricity supply provided in the JRC dataset with its explicit representation of discrete power technologies which are central to coal phaseout policies.

¹⁹ A detailed algebraic exposition of the generic multi-region multi sector CGE model is provided in Böhringer et al. (2018).

²⁰ We do not model transmission capacities explicitly. However, even with high Armington elasticities for electricity trade between EU regions (16 between domestic and imported electricity, and 32 between different importing regions), trade is limited by the initial trade volumes due to the CES structure.

²¹ As a starting point, the JRC dataset builds upon the GTAP database which in its latest version covers 141 regions and 65 sectors of the global economy for the base-year 2014 (Aguiar et al., 2019).

²² The projected input-output tables provide a holistic picture of the future economy and energy system reflecting a common sense business-as-usual development. The input-output tables for future years are constructed using a RAS balancing procedure that ensures consistency of various data sources within a multi-region accounting framework (Rey Los Santos et al., 2018).

The regional coverage in our composite dataset used for model simulations reflects our focus on coal phaseout in Europe. The European Union is divided into 12 regions, based on country size, geographical location and policies regarding coal phaseout. For the sake of compactness, we limit the explicit representation of other regions to one non-EU European region, three major EU trading partners (USA, Russia, China), while treating the remainder of the global economy through a composite region Rest of the World.

Table 3 provides an overview of the sectors (incl. power technologies) and regions that are represented in our model.

Table 3. Sectors and regions in the CGE model (acronyms provided in brackets)

<i>Sectors and commodities¹</i>	<i>Countries and regions</i>
<i>Primary energy sectors</i>	<i>EU countries/regions</i>
Coal (COA)	Germany (DEU)
Crude Oil (CRU)	United Kingdom + Ireland (GBR)
Natural Gas (GAS)	France (FRA)
<i>Emission-intensive and trade-exposed sectors</i>	Poland (POL)
Chemical Products (CRP)	Spain + Portugal (SPP)
Non-Metallic Minerals (NMM)	Italy + Malta (ITA)
Iron and Steel (I_S)	Greece + Cyprus (GRE)
Non-Ferrous Metals (NFM)	Belgium + Netherlands + Luxemburg (BNL)
Refined Oil (OIL)	Sweden + Denmark + Finland (SCA)
Paper Products, Publishing (PPP)	Bulgaria + Romania (SEU)
Air Transport (ATP)	Estonia + Latvia + Lithuania (BAL)
<i>Electricity generation and distribution</i>	Central European countries (CEU) ²
Coal-fired (TCOA)	<i>Non-EU countries/regions</i>
Oil-fired (TOIL)	Rest of Europe and Turkey (RET)
Gas-fired (TGAS)	United States of America (USA)
Nuclear (TNUC)	China (CHN)
Biomass (TBIO)	Russia (RUS)
Hydroelectric (THYD)	Rest of the World (ROW)
Wind power (TWIN)	
Photovoltaics (TSOL)	
Transmission and distribution (ELE)	
<i>Other sectors</i>	
Services (SER)	
All other goods (AOG)	

¹ All sectors except Transmission and distribution, Services and All other goods are regulated by the EU ETS

² CEU includes Austria, Czech Republic, Slovakia, Hungary, Slovenia and Croatia

3.2 Policy scenarios

In our policy scenarios, we focus on 2030 as a prominent milestone for EU climate policies. The benchmark situation in 2030 is captured by the JRC projections (Rey Los Santos et al. 2018) on economic activity and CO₂ emissions as the announced EU climate policy legislations will have been implemented. Most importantly, the benchmark situation reflects the official emissions targets for the EU in 2030, including the EU ETS with an emissions cap of 43% below the emissions level in 2005.

More recently, however, the EU commission has pushed for more rigorous emissions reductions as communicated in the European Green Deal (European Commission, 2019). In line with this policy initiative, we construct a reference (*REF*) scenario assuming that the emissions caps, both in the EU ETS and in Non-ETS in all EU countries, are reduced by 10% from the initial benchmark level in 2030. Our CGE simulation of the *REF* scenario suggests that the ETS price further increases to 47 Euro per ton CO₂, to comply with the more stringent emissions cap.²³

Throughout our numerical analysis, we measure the impacts of counterfactual phaseout policies against the reference (*REF*) scenario. In line with our theoretical analysis, we consider a range of coal phaseout scenarios (taking the *REF* scenario as a starting point) as listed in Table 4. First, we distinguish on the regional coverage of the coal phaseout: The phaseout can take place as a unilateral action of a single region (*UNI*) or a multilateral phaseout by a coalition of regions (*COA*). Second, we adopt different assumptions on the cancellation of ETS allowances that go along with the coal phaseout: There might be no cancellation of allowances, unilateral cancellation (*UC*) on behalf of the country phasing out coal, or centralized cancellation via the Market Stability Reserve (*MSR*).

Table 4. Coal phaseout scenarios for 2030

		Cancellation of allowances		
		None	Unilateral	Centralized via MSR
Regional coverage	Unilateral	<i>UNI</i>	<i>UNI-UC</i>	<i>UNI-MSR</i>
	Coalition	<i>COA</i>	<i>COA-UC</i>	<i>COA-MSR</i>

In the unilateral scenarios, we focus on Germany as it has by far the biggest coal power generation in the EU (both currently and in our *REF* scenario for 2030).²⁴ Germany also has passed legislation for a premature phaseout coal power generation. We also present simulation results considering the unilateral coal phaseout of all other EU regions, irrespective of whether they have decided to phase out coal in electricity generation. For the multilateral phaseout coalition, we include all EU regions except POL and SEU, based on information about coal phaseout decisions or considerations (Agora Energiewende and Sandbag, 2020).²⁵

Cancellation of allowances (if any) follows the setup in the analytical model. We consider 100% cancellation ($\omega^U = 1$ and $\omega^A = 1$) in the figures, meaning that cancellation of allowances by the coal phaseout region(s) is equal to the emissions from the phased out coal power generation, but we also report the effects of 50% cancellation.²⁶ Instead of choosing specific price tags on emissions

²³ In the Non-ETS segments of the EU countries, national CO₂ prices are set sufficiently high to meet the Non-ETS targets. In all phaseout scenarios, national Non-ETS emissions remain constant, i.e., the national CO₂ prices are adjusted endogenously in line with the exogenous national Non-ETS targets.

²⁴ In 2018, Germany's share of coal power generation in the EU was slightly above one third (BP, 2019), while in our *REF* scenario it is around one half.

²⁵ The only EU countries that haven't yet decided to phase out coal are (by May 2020) the Czech Republic, where phaseout is under discussion, and Poland, Romania, Bulgaria, Slovenia and Croatia. Hence, as we only exclude POL and SEU from the coalition, we disregard that Slovenia and Croatia (which are part of CEU) do not have plans to phase out coal. However, these countries are quite small in terms of (coal) power production.

²⁶ 100% cancellation via the MSR may seem overly optimistic but is included to ease the comparison with unilateral cancellation. Perino (2018) assesses that one unit additional emissions reduction in 2020 reduces the long-term emissions cap by 0.4-0.8 tons (via the MSR). Gerlagh et al. (2019) find that the long-term cap is

ourselves (i.e., valuations per ton emissions reductions, cf. discussion leading up to equation (11), including footnote 12), we show how the welfare impacts depend on price tags over a continuum of values.

The allocation of emissions allowances per EU region is exogenous and determined as follows: 43% of the allowances (corresponding to the freely allocated allowances in the EU) are distributed proportional to the region's emissions in non-electricity ETS sectors in the *REF* scenario. The remaining allowances are distributed following the EU rules for sharing of auctioned allowances.²⁷

In the phaseout scenarios, we consider both gradual and full phaseout of coal power, with either 25%, 50%, 75% or 100% exogenous reduction of coal power generation (*vis-à-vis REF*) in the region(s). For the sake of brevity, our results discussion below is restrained to a full phaseout, i.e., a 100% reduction of coal power generation (unless otherwise stated).

3.3 Numerical results

We first present and discuss scenarios where only Germany phases out coal. Then we consider briefly unilateral phaseout in other EU regions, before turning to the coalition scenario where several EU countries jointly phase out coal.

Unilateral coal phaseout in Germany

In the *REF* scenario with an EU ETS price of 47 Euro per ton CO₂, roughly a quarter of Germany's power generation still stems from coal-fired power plants. Hence, ETS emissions in Germany drop substantially as it phases out coal (by around 40% in the three unilateral scenarios considering alternative cancellation policies).

In the *UNI* scenario, where total ETS emissions remain constant at the binding overall ETS cap, emissions are simply re-allocated within the ETS via the so-called waterbed effect. Germany's coal phaseout induces an ETS price drop from 47 to 31 Euro per ton. As a result, ETS emissions in other parts of the EU increase (by 15% in total). The biggest relative increase is in Poland (30% increase), followed by other eastern and southern EU countries, mainly because these countries have a larger share of coal power generation than most of the western and northern EU member states and therefore expand coal power generation more markedly as a consequence of depressed ETS allowance prices. Relocation of emissions within the electricity sector is much bigger than relocation to other ETS sectors in the EU, but the share of ETS emissions in the electricity sector declines from 36% to 33%.

With 100% cancellation of emissions allowances released by Germany's coal phaseout, emissions in other EU countries hardly change. The ETS price increases slightly from 47 to 49 Euro per ton in both *UNI-UC* and *UNI-MSR*. As explained in our theoretical analysis in Section 2, it is a priori ambiguous whether the price goes up or down in this case. Emissions in most neighboring countries increase slightly due to increased net exports of electricity to Germany, while emissions in other EU countries

reduced by 0.9 tons if the reduction takes place in 2020 but can be *increased* if the reduction takes place a couple of decades later (see also Rosendahl, 2019).

²⁷ 88% of the auctioned allowances are distributed across member states according to their historic emissions, 10% are distributed to member states with comparably low GDP per capita, and 2% to "early movers". For more details, see https://ec.europa.eu/clima/policies/ets/auctioning_en#tab-0-2

slightly drop due to the higher ETS price.²⁸ With 50% cancellation, emissions outside Germany increase but less than in the *UNI* scenario, and the ETS price declines to 40 Euro.

When Germany phases out coal, the electricity price in Germany increases (by 6% in *UNI* and 7% in *UNI-UC* and *UNI-MSR*). As a consequence, other power generation technologies increase their output pending on the technology-specific supply elasticities and carbon intensities (note that nuclear power generation in Germany by 2030 is already phased out according to policy legislation). The share of renewable electricity increases from 64% to 84-85% across the three alternative cancellation policies for emissions allowances. Gas power increases its generation even for the case of unilateral allowance cancellation (*UNI-UC*) or centralized allowance cancellation via the MSR (*UNI-MSR*) despite of higher ETS prices. Net electricity import increases, too, from close to zero in the *REF* scenario to around 6% of domestic consumption in the *UNI* scenario. Electricity prices in other EU countries go either up or down in this scenario. In countries with much coal power generation (e.g., Poland), the price drops due to lower ETS price, while in countries with little fossil-based power generation (e.g., France), the price increases slightly due to increased electricity exports to Germany.

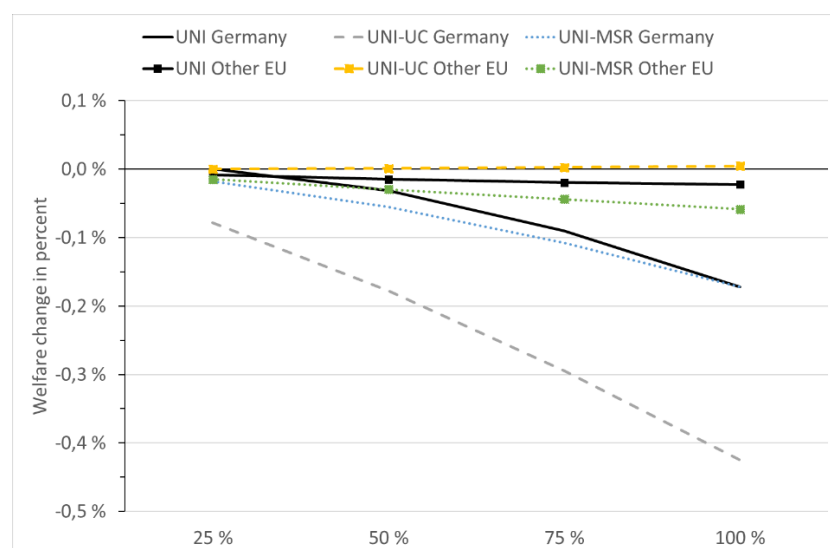
Next, we turn to welfare (measured in terms of Hicksian equivalent variation of income), and first disregard valuation of emissions reductions. Figure 2 shows the welfare impacts for Germany and a composite of all other EU countries (labeled ‘Other EU’). As expected (see also Proposition 1), Germany’s welfare decreases in the *UNI* scenario – by 0.17% under complete phaseout. In monetary terms, this amounts to a loss of 4 billion Euros. However, we also notice that a limited phaseout of 25% *increases* German welfare, although only marginally. The explanation is terms-of-trade benefits in the ETS market. In the *REF* scenario, Germany is a net importer of allowances. As the country starts to phase out coal, the ETS price declines and the lower costs of importing allowances dominate the higher costs of electricity generation. With more extensive phaseout, however, the latter costs dominate. In addition, Germany turns into a net exporter of allowances under complete phaseout.

If Germany also cancels allowances alongside with the coal phaseout, economic costs further increase by another 0.25 percentage points, or additional 5.5 billion Euros. The obvious reason is that Germany loses income from sales of allowances. However, the additional welfare costs are around 25% higher than the direct income loss from these sales (calculated as the product of canceled allowances times the allowance price under complete phaseout without cancellation). One explanation is again terms-of-trade changes in the ETS market. As coal power is phased out in the *UNI* scenario, Germany becomes a net exporter of allowances while the ETS price drops significantly. In the *UNI-UC* scenario, however, the country again becomes a net importer of allowances and the ETS price increases significantly (especially vis-à-vis *UNI* but also vis-à-vis *REF*). Hence, cancellation induces terms-of-trade losses for Germany in the ETS market (see Proposition 2 and second term in equation (14)). In the *UNI-MSR* scenario, when emissions allowances are instead reduced via the MSR and the loss in auction revenues is shared among all member states, Germany’s welfare loss is almost the same as in the *UNI* scenario (i.e., the case without allowance cancellation). Germany is then a net exporter of allowances and benefits from higher ETS price, which compensates its foregone auction revenues.

²⁸ There are a few slight deviations from the analytical findings in Tables 1-2. In Table 2, emissions in regions that do not phase out coal go down if the ETS price increases, while in our simulations the emissions effect can go both ways. Similarly, electricity prices might go up or down across different regions, reflecting the possibility of cross-country electricity trade in our CGE framework (which we disregarded in Section 2).

For the other EU countries, the results are mixed. Countries that are initially net exporters of allowances, see some welfare reductions in the *UNI* scenario due to terms-of-trade losses in the ETS market as the ETS price is reduced by one third. This includes all eastern, southern and northern EU regions except Italy and Poland. For countries that are not exporters of allowances, we would expect some welfare gains from the German coal phaseout (see Proposition 1). This is certainly the case for Italy, which is a net importer of allowances, but also for Poland, which has no initial trade in allowances.²⁹ For the composite of other EU countries, we see from Figure 2 that they are worse off in terms of economic welfare. If Germany cancels allowances, however, other EU countries are on average slightly better off than without any phaseout, and hence better off than without cancellation. The terms-of-trade effects in the ETS market is turned around as the ETS price increases instead of decreases. If allowances are instead cancelled via the MSR, all EU regions lose since the losses in auction revenues dominate any terms-of-trade benefits in the ETS market.

Figure 2. Welfare effects of coal phaseout for Germany and the rest of the EU in *UNI*, *UNI-UC* and *UNI-MSR* scenarios (% from *REF*) without emissions valuation



The main motivation behind phasing out coal is the cutback of CO₂ emissions from fossil fuel combustion in order to mitigate climate change. Hence, it is also important to account for the benefits of any reductions in CO₂ emissions. However, as pointed out in Section 2, it is difficult to know the valuation per ton emissions reduction, not least from the perspective of the country (or countries) that phases out coal. On the one hand, one could argue that the value must exceed the ETS price, if a country decides to implement measures that are likely to have marginal abatement costs exceeding this price (and may even risk the waterbed effect unless it is followed by cancellation of allowances). On the other hand, the climate damage costs of CO₂ for a single country is likely to be small unless it accounts for the global damage costs of its emissions. There are also other relevant issues here, which we return to in the conclusions.

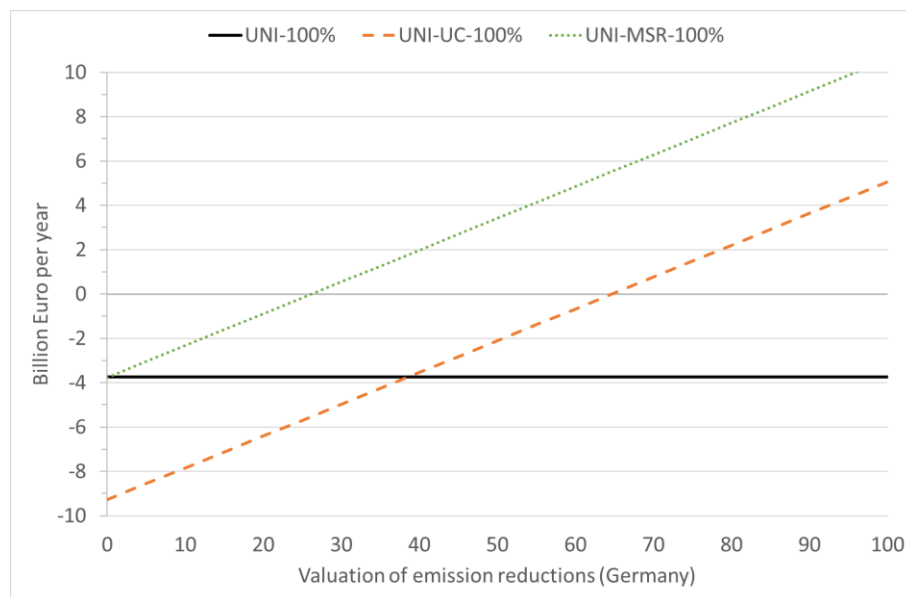
Instead of picking a specific number, we show in Figure 3 the welfare effects for Germany as a function of the country's valuation of emissions reductions under complete phaseout. The welfare

²⁹ The three western regions (GBR, FRA and BNL), who are small importers of allowances, see minor welfare losses which may be due to terms-of-trade losses in other markets such as the electricity market (e.g. GBR and BNL are importing electricity and face higher electricity prices).

effects on the y-axis correspond to the numbers reported in Figure 2. In the *UNI* scenario, the welfare effects are insensitive to the value of emissions as total emissions do not change vis-à-vis *REF*. In the *UNI-UC* and *UNI-MSR* scenarios, however, the welfare effects improve towards higher valuations of emissions reductions.

First, we notice that *given a decision to phase out coal*, unilateral cancellation of allowances is welfare-improving for Germany if the country values CO₂ emissions reductions by at least 39 Euro per ton, i.e., 8 Euro below the ETS price in the *REF* scenario. From Propositions 1 and 2 we know that with a *marginal* reduction in coal power generation, a country should cancel allowances if and only if it values emissions reductions higher than the ETS price. With inframarginal reductions of coal power generation, cancellation of emissions allowances reduces the downward pressure on the ETS price. This explains why a lower price tag on emissions is required to make cancellation advantageous under full phaseout compared to partial phaseout.

Figure 3. Welfare effects of coal phaseout in Germany in *UNI*, *UNI-UC* and *UNI-MSR* scenarios as a function of valuation of emissions reductions (% from *REF*)



Second, we see that for the joint policy of coal phaseout and unilateral allowance cancellation to be welfare-improving as compared to the *REF* scenario, Germany's value of emissions reductions must exceed 65 Euro per ton. Thus, from the figure we can conclude that if Germany values emissions reductions by 65 Euro per ton or more, complete phaseout is better than no phaseout when combined with cancellation of allowances (according to our simulations). Thus, referring to Figure 1 in Section 2, we are likely in the "Medium initial gains" case if the price tag is slightly higher than 65 Euro per ton (and "Low initial gains" if the price tag is slightly below 65 Euro). But what is the optimal rate of phaseout for different price tags? This is illustrated in Figure C1 in Appendix C. There we see that the first unit of coal phaseout is welfare-improving for Germany if its price tag exceeds 40 Euro per ton,³⁰ while complete phaseout is the optimal choice if the price tag is 83 Euro per ton or higher.

³⁰ The reason why the required price tag of 40 Euro is lower than the initial ETS price of 47 Euro is again terms-of-trade benefits for Germany in the ETS market (see above). Note further that Figure C1 assumes cancellation of allowances. As shown above (e.g. Figure 2), without cancellation it is optimal with a limited phaseout even though emissions remain unchanged. The optimal phaseout rate is then 15%, and this will be the best solution

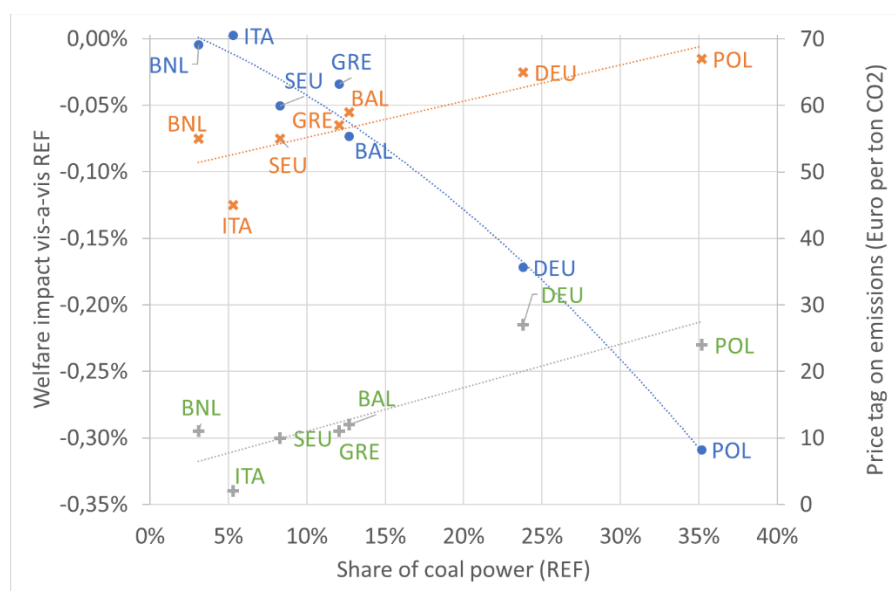
If Germany instead can rely on the MSR to take care of cancellation, coal phaseout is welfare-improving for Germany already if its price tag on emissions exceeds 27 Euro (assuming 100% cancellation), see Figure 3.³¹ As the losses in auction revenues are spread across EU member states, a much lower price tag on emissions is required to make coal phaseout welfare-improving for Germany (compared to unilateral cancellation).

Unilateral coal phaseout in other EU regions

Apart from Germany, there are other EU member states that have decided or are considering phasing out coal power generation. We thus compare the effects of unilateral coal phaseout in each of our EU model regions (*UNI* scenarios).

The share of coal power in the power mix varies substantially across EU regions in the *REF* scenario, from less than 0.1% in France to 35% in Poland. We should expect bigger welfare impacts from a coal phaseout in countries with a large share of coal power than in countries with a low share (at least in the scenario without cancellation and thus no effect on total emissions). This is indeed the case, as shown in Figure 4 (blue dots), where we only display regions with more than 2% coal power share in the *REF* scenario. Poland has the biggest costs, with a welfare loss of 0.3%. When plotting a polynomial trendline of second order, we see that the welfare costs curve is slightly convex in the share of coal power. This is intuitive as the marginal costs of reducing power generation from a certain technology typically increases with the extent of reduction. The two regions that are above the trendline (ITA and GRE) both have bigger shares of gas power than the EU average. With lower ETS prices from coal phaseout, gas power generation benefits, limiting the welfare costs in these regions.

Figure 4. Welfare effects of coal phaseout in different EU regions in *UNI* scenario, and required price tag on emissions in *UNI-UC* and *UNI-MSR* scenarios*



for Germany for price tags below 49 Euro per ton. For higher price tags, phaseout combined with cancellation is the best choice.

³¹ As mentioned before, 100% cancellation of allowances via the MSR may not be realistic, although it is difficult to know how effective the MSR will be in killing allowances. If we instead assume 50% cancellation via the MSR, the price tag on emissions must be 51 Euro per ton to make coal phaseout welfare-improving for Germany.

* The blue dots show welfare impacts in the *UNI* scenarios (left axis), the red x's show the required price tag on emissions in the *UNI-UC* scenarios (right axis), while the green +'s show the required price tag on emissions in the *UNI-MSR* scenarios (right axis)

The figure also shows how big the price tag on emissions must be in order to make coal phaseout welfare-improving in the *UNI-UC* (red x) and *UNI-MSR* (green +) scenarios. Intuitively, the required price tag is higher in the former case (38-47 Euro per ton higher), where the acting region cancels allowances unilaterally; in this case the required price tag is above the ETS price for all regions except Italy. With cancellation via the MSR, the required price tag is significantly below the ETS price for all regions shown. In both cases, there is an increasing trendline, suggesting that regions with large amounts of coal power face higher unit abatement costs (Euro per ton reduced) than regions with little coal power when phasing out coal completely. This is intuitive given the convex costs of phasing out coal, as explained above.

Multilateral coal phaseout by coalition

We now turn to the *COA* scenarios, where most EU member states jointly phase out coal. The only exceptions are Poland (POL), Romania and Bulgaria (SEU) – the few EU countries which have not communicated plans for a coal phaseout. Compared to unilateral phaseout, there are several important differences. First and not surprisingly, the extent of emissions reduction from a collective coal phaseout is much bigger. Hence, the ETS price drops from 47 Euro per ton in the *REF* scenario to 16 Euro per ton with complete phaseout and no cancellation (*COA* scenario). Second, there is less relocation of emissions to non-coalition countries which in the *COA* scenarios only consists of three countries. On the other hand, there is more relocation of emissions within the coalition (both more gas power generation and more emissions in energy-intensive industries), due to the substantial decline in the ETS-price. This relocation is slightly higher than relocation to non-coalition countries. Six of the ten coalition countries (e.g. the UK and France) actually have higher emissions under coal phaseout than in the *REF* scenario, as their share of coal power is already very low.

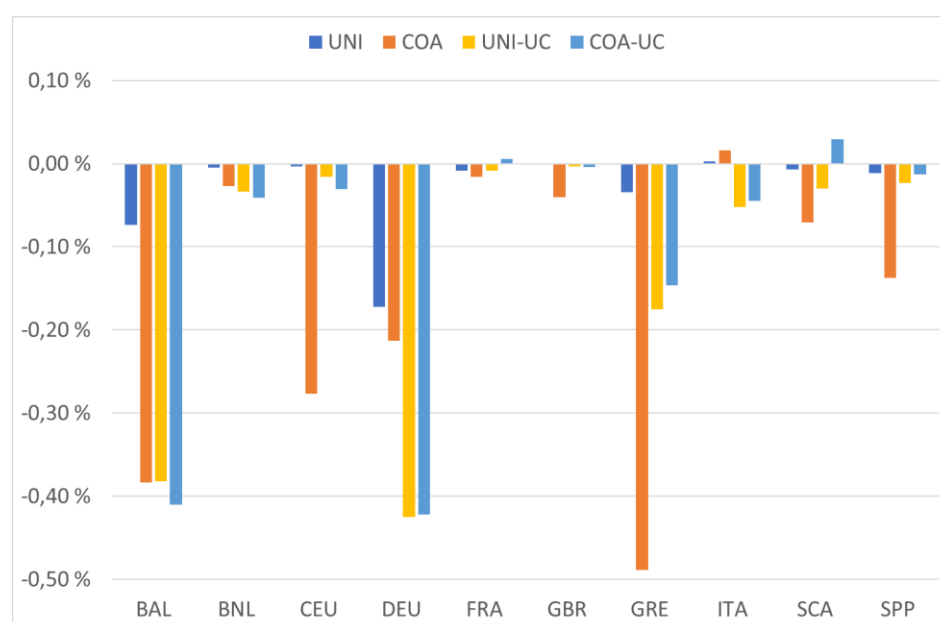
With cancellation of allowances, either by the coalition (*COA-UC*) or via the MSR (*COA-MSR*), ETS emissions are reduced by 15% and the ETS price increases to 50 Euro per ton. There is only negligible relocation of emissions to non-coalition regions, while relocation within the coalition is substantially reduced.

Turning to welfare, Figure 5 shows welfare effects for the coalition members when environmental valuation is disregarded, both under unilateral and coalition phaseout and with and without cancellation (thus, the leftmost bars for each region in Figure 5 correspond to the blue dots in Figure 4 above). In the cases without cancellation, we see that all regions except Italy are worse off when other regions join compared to when these regions act alone.³² Italy is the only region that actually benefits (marginally) from phasing out coal unilaterally. As mentioned above, Italy is a net importer of allowances and benefits from lower ETS price. These benefits increase when more countries phase out coal in the *COA* scenario and the ETS price drops further. On the other hand, regions like GRE, CEU, BAL, SPP and SCA are large exporters of allowances (relative to their emissions), and hence face much higher welfare costs in the *COA* scenario compared to when they phase out coal unilaterally, due to less export revenues in the ETS market (see the figure). In Figure C2 in Appendix C we plot the welfare difference between *COA* and *UNI* versus the initial net export of allowances (as

³² In the analytical section (Proposition 4), we concluded that for a region that has already decided to reduce its coal power generation, its welfare impact of a second region making the same decision is ambiguous.

a share of emissions), showing a clear negative relationship.³³ For the coalition as a whole, welfare is reduced by 0.1% from the *REF* scenario, or 11 billion Euro per year (i.e., 7 billion Euro more than with only German coal phaseout).

Figure 5. Welfare effects of unilateral and multilateral coal phaseout. Percent change vis-a-vis *REF**



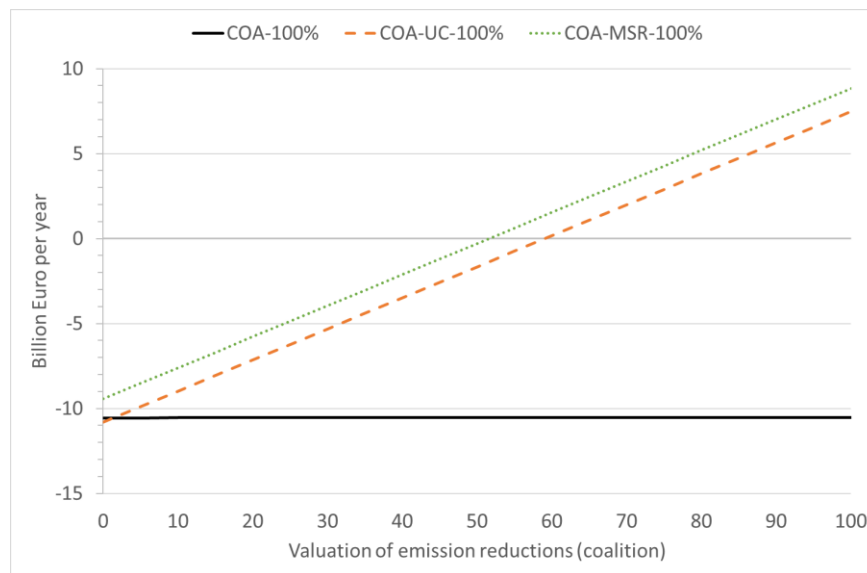
* Valuation of emissions reductions is here disregarded

With cancellation, however, the pattern is changed. Around half of the regions are better off when other regions join, while the other half are worse off (before accounting for additional environmental benefits). In particular, GRE and SCA are better off now that the ETS price increases instead of decreases. SCA also benefits via higher prices in the electricity market when more regions phase out coal, as Scandinavia is a large exporter to e.g. Germany.

Last but not least, we examine how the welfare effects for the coalition as a group are affected when we add the benefits of reduced CO₂ emissions, see Figure 6. There are several differences vis-à-vis the corresponding Figure 3 for Germany in the unilateral scenarios. First, given a decision to phase out coal completely, supplementing with cancellation of allowances improves coalition welfare if its value of emissions exceeds merely 2 Euro per ton. Further, the combined policy of complete phaseout and unilateral cancellation is welfare-improving for the coalition (compared to no phaseout) if the value of emissions exceeds 60 Euro per ton, i.e., slightly lower than the corresponding value in the unilateral scenario for Germany (65 Euro). With cancellation via the MSR, the required price tag for the coalition is 52 Euro per ton, i.e., much higher than in the *UNI-UC* scenario for Germany. This is intuitive as the coalition consists of most EU regions and hence most of the reduced auction volumes fall on the coalition members also in the *COA-MSR* scenario.

³³ The trendline suggests that for every 25 percentage points increase in net export of allowances, the welfare costs of other region's phaseout in the *COA* scenario increase by 0.1 percentage points.

Figure 6. Welfare effects of coal phaseout in the coalition in *COA*, *COA-UC* and *COA-MSR* scenarios. Percent change vis-a-vis *REF*



3.4 Sensitivity analysis

The simulation results presented above hinge on some uncertain parameters, and thus in this subsection we present some sensitivity analysis focusing on unilateral coal phaseout in Germany. We consider alternative assumptions about i) supply elasticities for electricity technologies and ii) trade (Armington) elasticities for electricity. In both cases, we consider the effects of either halving or doubling the elasticities in all regions and for all technologies. In addition, we examine how sensitive the effects of phaseout are to the initial emissions cap in the *REF* scenario. In the simulations above, the emissions cap in the *REF* scenario is 10% below the cap in the *BMK* scenario (which is consistent with EU's Paris target). Here we set the *REF* cap equal to respectively the *BMK* cap, and 20% below the *BMK* cap. We focus on the welfare costs for Germany in the *UNI* scenario (without cancellation), and the required price tag on emissions to make coal phaseout with cancellation welfare improving (i.e., the same type of information as in Figure 4, except that we skip the MSR scenario).

The results of the sensitivity analysis are displayed in Table 5. As expected, the welfare costs of coal phaseout in Germany increase with lower supply elasticities for electricity technologies – by more than 50% when elasticities are halved. With higher elasticities, welfare costs decrease but much less. The reason is that with low supply elasticities, the share of coal power is higher in the *REF* scenario compared to in the main simulation (due to less responsiveness to the CO₂ price), and hence the costs of phaseout are higher both due to a bigger initial share of coal power and due to higher costs per unit reduction. The required price on emissions to make coal phaseout *with* cancellation welfare-improving also increases by around 50% if supply elasticities for electricity technologies are halved.

For trade elasticities, the results are not as obvious. With lower elasticities, the welfare costs are slightly reduced, while with higher elasticities costs are slightly increased. One reason is that the share of coal power in Germany in the *REF* scenario is slightly higher with higher trade elasticities, and hence the costs of complete coal phaseout increase. A second reason is that Germany is a net exporter of electricity in the *REF* scenario, and thus has some terms-of-trade benefits in the electricity market when coal phaseout leads to higher electricity prices. This price effect is biggest

when trade elasticities are low. The required price on emissions is not much changed, though, when changing the trade elasticities.

Table 5. Sensitivity analysis for unilateral coal phaseout in Germany*

	Welfare effect <i>UNI</i> (vis-à-vis <i>REF</i>)	Price tag <i>UNI-UC</i> (Euro per ton CO ₂)
Main simulation	-0,17 %	65
Lower supply elasticities	-0,27 %	94
Higher supply elasticities	-0,14 %	49
Lower trade elasticities	-0,14 %	62
Higher trade elasticities	-0,21 %	69
Lower emissions cap	-0,09 %	75
Higher emissions cap	-0,28 %	56

* Lower and higher elasticities mean respectively 50% lower and 100% higher elasticities.

Lower emissions cap means 20% below the *BMK* scenario, while higher cap means exactly the *BMK* scenario

Finally, if the emissions cap is lower (20% below *BMK*), welfare costs are halved as the initial share of coal power in the *REF* scenario is lower (19% versus 24% in the main simulation) and the remaining coal power (before phaseout) is less profitable due to much higher ETS price. With higher emissions cap (*REF* equal to *BMK*), welfare costs are instead increased by more than 50% (initial share of coal power is then 28%). For the required price tag, however, the effects are turned around, as with the higher emissions cap, much more emissions allowances are cancelled and hence the emissions reductions are much bigger.

4. Conclusions

Most countries in the EU have decided or announced to phase out coal from their electricity generation as a commitment to stringent climate policy. However, such phaseout initiatives come on top of the EU Emissions Trading System (EU ETS) which is already regulating emissions from the electricity sector. Overlapping regulation may lead to unintended economic and environmental impacts that may undermine the primary policy objectives. One important issue is whether coal phaseout is affected by the so-called waterbed effect, i.e., that emissions are simply relocated between EU countries under the EU emission cap rather than reduced.

In this paper, we have examined theoretically and numerically the consequences of phasing out coal power, both for the electricity markets, countries' economic welfare, and CO₂ emissions. We show that impacts are critically hinging on whether coal phaseout is followed by cancellation of emissions allowances, and whether a country goes alone in phasing out coal or together with other countries.

In our theoretical analysis, we have derived how the domestic welfare impacts for the phaseout region depend on i) whether and how emissions allowances are canceled, ii) whether or not other countries phase out coal as well, and iii) terms-of-trade effects in the ETS market. If allowances are canceled, the welfare impacts for the phaseout region crucially depend on the region's price tag on emissions, but it also depends on who pays for the cancellation via reduced auctioning. Intuitively, unilateral cancellation is more costly than joint cancellation such as via the Market Stability Reserve (MSR) in the EU ETS. In the former case, a marginal reduction in coal power is welfare improving (for symmetric regions) if the region values additional emissions reductions higher than the ETS price.

Our numerical analysis based on a computable general equilibrium (CGE) model of the European economy has shown that the economic welfare costs of coal phaseout depend crucially on the initial market share of coal power in a country's electricity sector. Hence, Germany is more affected than most other countries, with a non-negligible welfare loss in the case without cancellation. Furthermore, we find that most other EU countries face some welfare losses, as most of these countries are net exporters of emissions allowances and face lower emissions prices as Germany phases out coal. Unilateral cancellation of allowances adds additional costs to Germany, but also net emissions reductions in the EU. Hence, cancellation is welfare improving for Germany if the country has already decided to phase out coal and values additional emissions reductions at 39 Euro per ton or more. Coal phaseout with cancellation is welfare-improving (compared to no phaseout) if this price tag is at least 65 Euro per ton. In the case where most EU countries phase out coal jointly, we find that most EU countries are worse off than when acting alone. Again, this is due to terms-of-trade effects in the ETS market, as the ETS price drops substantially if many countries phase out coal.

Phasing out coal can have different motivations, as briefly touched upon in the introduction. In our paper, we have focused on the impacts on CO₂ emissions in addition to economic welfare effects. However, we have not taken into account possible long-term and indirect effects on CO₂ emissions via speeding up the transition to CO₂-free energy and technology (see e.g. Rozenberg et al., 2020), and hence reduce the costs of reaching long-term targets. For instance, Goulder (2020) is concerned about speeding up CO₂ abatement, and argues that "consideration of the prospects for near-term implementation justifies giving alternative approaches [to carbon pricing] a closer look". In the European Green Deal, the European Commission (2019) proposes to reach net zero CO₂ emissions by 2050. If countries are more concerned about domestic emissions than European or global emissions (Newbery et al., 2019), the case for coal phaseout is increased. Phasing out coal can also reduce emissions of other local and regional pollutants such as NO_x, SO₂ and particles, and hence reduce the health and environmental damages from such pollution (Ščasný et al., 2015). On the other hand, phasing out coal in Europe may increase the reliance on imported gas, which has long been an energy security issue in several European countries (Aune et al., 2017), and increased share of intermittent electricity technologies may lead to challenges with regards to grid stability (Geske and Green, 2020). These benefits and costs are not incorporated in our analysis.

Last but not least, there are distributional impacts not only between countries, but also within coal phaseout countries. This is especially evident in Germany, where there is much talk about a "just transition" away from coal (Oei et al., 2019). The coal commission proposed a number of measures to help coal regions transition away from coal and towards activities that are more sustainable in the long run.

Coal phaseout is on the agenda not only in Europe, but in several other (mainly OECD) countries, too (Littlecott and Webb, 2017). We have pointed to many issues relevant to coal phaseout above, while in our analysis we have centered on possible interactions with an ETS. As emissions trading is implemented in many countries around the world, our analysis should be relevant also beyond the European context focused on in our paper.

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Appendix A. Analytical derivations

Here we derive the effects of a marginal reduction in the use of coal power ($dy_{1,C}^E < 0$). For that purpose, we differentiate first order conditions and equilibrium conditions above.

No change in emissions cap

From (2) we get the changes for electricity producers:

$$(20) \quad dp_r^E = c_{r,j}^E (y_{r,j}^E) dy_{r,j}^E + \sigma_j dp^Q$$

From (4)-(6) we get the changes for the industry producers:

$$(21) \quad \partial^2 c_r^I / \partial y_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial y_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial y_r^I \partial q_r^I \cdot dq_r^I = 0$$

$$(22) \quad \partial^2 c_r^I / \partial e_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial e_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial e_r^I \partial q_r^I \cdot dq_r^I = dp_r^E$$

$$(23) \quad \partial^2 c_r^I / \partial q_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial q_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial q_r^I \partial q_r^I \cdot dq_r^I = dp^Q$$

From (8)-(10) we get the changes for the consumers, as well as the changes in the electricity and quota markets, respectively:

$$(24) \quad dp_r^E = u_r^C (e_r^C) de_r^C$$

$$(25) \quad \sum_j dy_{r,j}^E = de_r^I + de_r^C$$

$$(26) \quad \sum_r \left(\sum_j dq_{r,j}^E + dq_r^I \right) = \sum_r dQ_r = 0$$

Note first that the only link between the countries goes via the quota market and the quota price. Assume first that the quota price remains unchanged, so that countries 2 and 3 are unaffected by the reduced coal power production in country 1. To restore equilibrium in country 1's electricity market (cf. (25)), the domestic electricity price must increase: $dp_1^E > 0$. From (22) and (24) we then get $de_1^I < 0$ and $de_1^C < 0$,³⁴ while from (20) we get $dy_{1,j}^E > 0$ for all j except coal. Gas power production in country 1 will increase, but less than the decrease in coal power (since total power production must fall in line with lower total power consumption).

In industry production, reduced electricity use will be followed by reduced output and reduced emissions (cf. (21) and (23)).³⁵ Emissions in the power sector drops as the drop in coal power production is bigger than the increase in gas power production, and coal is more emissions intensive than gas. Hence, we must have $dQ_1 < 0$. We then get excess supply in the quota market (26), and hence the quota price drops, $dp^Q < 0$.

³⁴ We here assume that the direct price effect in (22) dominates any indirect effects via changes in output and/or emissions caused by the electricity price increase.

³⁵ Remember that the cross-derivatives are assumed to be negative. Hence, the second terms in (21) and (23) are positive. Since $\partial^2 c / \partial y \partial y \cdot \partial^2 c / \partial q \partial q - 2 \partial^2 c / \partial y \partial q > 0$ (see the main text), and the two prices are assumed to be unchanged, we must have $dq_1^I < 0$ and $dy_1^I < 0$.

In country 1, this has second-order effects as follows: Gas power production increases its production (and emissions) further, cf. (20), i.e., $dy_{1,G}^E > 0$, reducing the electricity price somewhat. The price reduction cannot exceed the initial price increase though, as the price reduction is a second-order effect caused by the initial price increase. Hence, we will still have $dp_1^E > 0$ (compared to the initial situation). Industry emissions increase, that is, the initial decrease in emissions is counteracted (partly or wholly), first of all due to the lower quota price (cf. (23)) but also to some degree due to the reduced increase in the electricity price (cf. the discussion above). Compared to the initial situation, the electricity price is higher while the quota price is lower, and we cannot say unambiguously whether industry emissions in country 1 increase or decrease. We must still have $dQ_1 < 0$ though, as this second order effects on industry emissions was caused by the lower quota price, which again was driven by $dQ_1 < 0$.

In countries 2 and 3, the lower quota price stimulates production and emissions of coal power (cf. (20)), putting a downward pressure on the electricity price. Gas power production is stimulated by the lower quota price, while lower electricity price goes in the opposite direction (cf. (20)) – hence we cannot say whether gas power production in countries 2 and 3 increases or decreases.

Renewable power production will fall (cf. (20)), while from (22) and (24) we get $dx_r^I > 0$ and $dx_r^C > 0$ for $i = 2, 3$. Emissions in the industry sectors of these countries are increased both due to lower quota price and lower electricity price. Emissions in the electricity sectors also increase, as total power production increases, and there is a shift towards more emission-intensive generation. Thus, $dQ_r > 0$ for $r = 2, 3$.

Change in emissions cap

Next we consider the case where country 1 cancels allowances corresponding to the emissions from the reduced coal production, that is, $d\bar{Q}_1 = \sigma_c(dy_{1,C}^E) < 0$. Following the procedure above, we first assume no changes in the quota price. Then the effects obviously are the same as discussed above (i.e., for $dp^Q = 0$). The net effects on the ETS is however unclear, as the reduced emissions from coal power is exactly matched by reduced supply of quotas. What matters now is whether or not higher emissions from gas power production dominates lower emissions from industry production. This is in general ambiguous, and can typically differ between countries, depending on the potential for gas power production and the industry structure of the country.

If the net effect on emissions in country 1 is the same as above (i.e., decreases), we get exactly the same qualitative results (but smaller quantitative effects). If emissions in country 1 instead increase, the quota price increases, and the effects in countries 2 and 3 become the opposite as above, and the same goes for the second order effects in country 1. Gas power production will still increase, but not as much as with unchanged quota price. Total emissions in the power sector will thus decrease. Industry emissions will now unambiguously fall, both due to higher electricity price and higher quota price. The other effects in country 1 are the same as before.

Appendix B. Numerical model description

The CGE model features a representative agent in each region who receives income from three primary factors: labor, capital, and technology-specific resources for coal, natural gas, crude oil and electricity generation. Labor and capital are inter-sectorally mobile within a region but immobile between regions. Technology-specific energy resources are specific to energy production sectors in each region.

All commodities except for fossil fuels and technology-specific electricity are produced according to a four-level nested CES cost function combining inputs of capital (K), labor (L), energy (E), and material (M).

At the top level, a material composite trades off with an aggregate of capital, labor, and energy. At the second level, the material composite splits into non-energy intermediate goods whereas the aggregate of capital, labor and energy splits into a value-added component and the energy component. At the third level, capital and labor inputs enter the value-added composite subject to a constant elasticity of substitution; likewise, within the energy aggregate, electricity trades off with the composite of fossil fuels (coal, natural gas, and refined oil). At the fourth level, a CES function describes the substitution possibilities between coal, refined oil, and natural gas.

Fossil fuel production is represented by a constant-elasticity-of-substitution (CES) cost function, where the demand for the specific resource trades off with a Leontief composite of all other inputs.

We distinguish different power generation technologies that produce electricity by combining inputs of labor, fuel, and materials with technology-specific resources (capital and natural resources such as water, sun, wind, biomass). For each technology, power generation takes place with decreasing returns to scale and responds to changes in electricity prices according to technology-specific supply elasticities. Within each region, electricity output from different technologies is treated as a homogeneous good which (only) enters as an input to the regional distribution and transmission electricity sector.

When it comes to supply elasticities for electricity technologies, very few empirical studies exist. We are only aware of Johnson (2014), who estimates such elasticities for renewable electricity in the U.S., finding a long-run supply elasticity of 2.67 (95% CI of 1.74, 3.60). Given the limited empirical findings, we consider equal elasticities across regions.³⁶ Further, we assume that coal and gas power are more elastic (for given fuel prices) than renewable power, which is more dependent on locations. We assume lowest elasticities for nuclear and hydro power. The assumed elasticities are shown in Table B1. The elasticities should be interpreted as medium- to long-term elasticities. As these are highly uncertain, we do sensitivity analysis related to these elasticities.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment and exogenous government provision of public goods and services. Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and a CES aggregate of other consumption goods. Substitution possibilities across different energy inputs in consumption are depicted in a similar nested CES structure as with production.

³⁶ Note that regions with large potential for a certain power production such as wind power will most likely have a quite large production level already in the calibrated *BMK* scenario, and hence respond more in absolute terms to electricity price changes compared to countries with more limited potential (despite equal supply elasticities).

Bilateral trade is modeled following Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington, 1969). Trade in electricity takes place only via the distribution and transmission electricity sector.³⁷ A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO₂ emissions are linked in fixed proportions to the use of coal, refined oil and natural gas, with CO₂ coefficients differentiated by fuels and sector of use. Restrictions to the use of CO₂ emissions in production and consumption are implemented through explicit emissions pricing of the carbon associated with fuel combustion either via CO₂ taxes or the auctioning of CO₂ emissions allowances. CO₂ emissions abatement takes place by fuel switching (interfuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final consumption activities).

Table B1. Assumed supply elasticities for electricity generation technologies (equal across regions)

Coal-fired (TCOA)	3
Oil-fired (TOIL)	1
Gas-fired (TGAS)	3
Nuclear (TNUC)	0
Biomass (TBIO)	2
Hydroelectric (THYD)	0.5
Wind power (TWIN)	2
Photovoltaics (TSOL)	2

³⁷ We do not model transmission capacities explicitly. However, even with high Armington elasticities for electricity trade between EU regions (16 between domestic and imported electricity, and 32 between different importing regions), trade is limited by the initial trade volumes due to the CES structure.

Appendix C. Numerical results – additional figures

Figure C1. Optimal coal phaseout rate in Germany in the *UNI-UC* scenario as a function of Germany's price tag on emissions

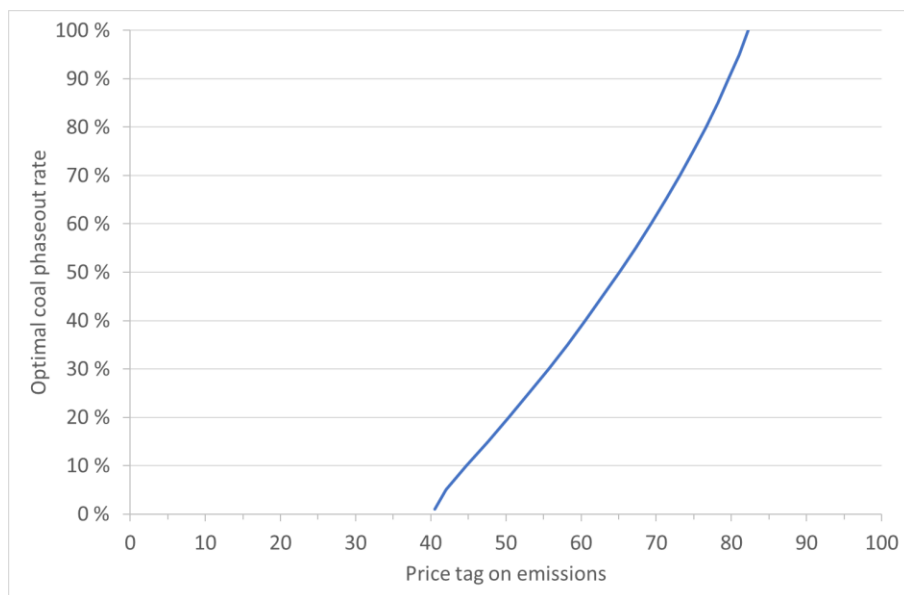


Figure C2. Plot of net export of allowances as share of emissions in the *REF* scenario versus welfare effects of the *COA* scenario relative to the *UNI* scenario for coalition regions

