Journal of Environmental Economics and Management 113 (2022) 102658

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Europe beyond coal – An economic and climate impact assessment

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ARTICLE INFO

JEL classification:
D61
F18
H23
Q54

Keywords:
Coal phaseout
Emissions trading
Electricity market

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, for CO_2 emissions, the electricity sector, and the broader economy. 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 phaseouts. We find that terms-of-trade effects in the ETS market play an important role for the welfare implications 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 CO_2 emissions reductions at 65 Euro per ton or more.

1. Introduction

In order to keep global warming below 1.5–2 °C, most of the global coal reserves have to be left in the ground (McGlade and Ekins, 2015; Welsby et al., 2021). Coal is the most carbon-intensive fossil fuel, and to date is also the dominant energy carrier in the electricity sector, with a market share of more than one third of global generation (BP, 2019). In the Glasgow Climate Pact (COP26 in 2021), which is a follow-up of the Paris Agreement (COP21 in 2015), countries around the world have agreed to "phasing down" coal (Vaughan, 2021). There are currently numerous policy initiatives throughout the world to phase out coal, especially in electricity generation.[1] As a prominent example, most EU member states have decided to phase out coal in power generation (Agora Energiewende and Sandbag, 2020). Switching away from coal power to other electricity technologies is often regarded as the cheapest carbon abatement option (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, an accelerated

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[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). Already in 2016, the world's biggest sovereign wealth fund, Norway's Government Pension Fund Global, decided to divest from coal companies (NBIM, 2016).

https://doi.org/10.1016/j.jeem.2022.102658
Received 7 July 2020; Received in revised form 18 November 2021; Accepted 30 March 2022
Available online 4 April 2022

phaseout of coal power may come with additional costs due to stranded investment, which must be traded off against the environmental benefits of CO_2 reduction.

In the EU, Germany is by far the biggest coal power producer (BP, 2019). The country has a long tradition in domestic coal mining, primarily justified by domestic energy security considerations (Storchmann, 2005; Herpich et al., 2018). While domestic hard coal extraction has meanwhile been terminated 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).

CO_2 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 response to 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; Bruninx et al., 2019).

In this paper we investigate the consequences of phasing out coal power generation by EU countries. We consider unilateral phaseout by individual EU countries such as Germany as well as joint phaseout by a coalition of several EU countries, examining economy-wide effects, changes in the electricity market, and impacts on CO_2 emissions.

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 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 German coal phaseout. However, we also consider unilateral phaseout in other EU countries as well as joint phaseout in various EU countries. The simulation results confirm basic intuition 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 adjustment costs. Most other EU countries are slightly worse off by German coal phaseout. The reasoning behind is that 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 without cancellation of allowances, 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. As a comparison, the German Environmental Agency (UBA, 2020) has proposed using 215 Euro per ton CO_2 (in 2030) when evaluating the damages of CO_2 emissions for public planning. If allowances are instead cancelled via the MSR, the required price tag is much lower.

Only a few papers so far 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 (2021) but they don't consider welfare gains from reduced emissions; furthermore, they do not provide quantitative estimates, 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. (2020b) 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, proposing that a faster phaseout would lead to a quicker economic recovery for the most exposed coal regions. Gerarden et al. (2020) apply a model of the US electricity market and examine 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 CO_2 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 SO_2. 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; Leroutier, 2021). 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. See also Fischer and Preonas (2010) for an early review of overlapping climate regulation.

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

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 limit 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. (2020a) discuss the German policies leading up to the recent coal phaseout decision, emphasizing the need to combine climate, energy, social, and structural policies. Based on a large-scale survey Rinscheid and Wüstenhagen (2019) conclude 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.[4] Likewise, ancillary benefits from reduced emissions of local and regional pollutants can provide an additional incentive (Ščasný et al., 2015; Rauner et al., 2020).

In Section 2 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) covering 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 $y^E_{r,j}$. We assume that CO_2 emissions from coal and gas power production is proportional to output, but with different emissions intensities σ_j: $q^E_{r,j} = \sigma_j y^E_{r,j}$. For each technology, the costs of electricity production are (in aggregate) a strictly convex function of output: $c^E_{r,j} = c^E_{r,j}(y^E_{r,j})$, with $c^{E\,\prime}_{r,j} > 0$ and $c^{E\,\prime\prime}_{r,j} > 0$. The profits of electricity producers in region r by technology j on competitive electricity markets are then given by:

$$\pi^E_{r,j} = p^E_r y^E_{r,j} - c^E_{r,j}\left(y^E_{r,j}\right) - p^Q q^E_{r,j} = \left(p^E_r - \sigma_j p^Q\right) y^E_{r,j} - c^E_{r,j}\left(y^E_{r,j}\right) \tag{1}$$

The industry sector (I) in each region is trading with the rest of the world at an exogenous world market price p^I.[5] Production and emissions of the industry sector in each region is denoted y^I_r and q^I_r, while the sector's use of electricity is denoted e^I_r. 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[6]: $c^I_r = c^I_r(y^I_r, e^I_r, q^I_r)$. The cost function is strictly convex in output, electricity use and emissions; the cross-derivatives are assumed to be negative,[7] 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 is:

$$\pi^I_r = p^I y^I_r - c^I_r\left(y^I_r, e^I_r, q^I_r\right) - p^E_r e^I_r - p^Q q^I_r \tag{2}$$

Consumers (and other sectors) also use electricity, denoted e^C_r, and their gross consumer surplus in the electricity market is an increasing and strictly concave function of electricity consumption: $u^C_r = u^C_r(e^C_r)$, implying declining marginal utility of consumption. Net consumer surplus is given by[8]:

$$\pi^C_r = u^C_r\left(e^C_r\right) - p^E_r e^C_r \tag{3}$$

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

$$\sum_j y^E_{r,j} = e^I_r + e^C_r \tag{4}$$

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

[5] Hence, we treat the industry market differently from the electricity market. Although this 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, gross trade in electricity amounts to a modest share of total electricity consumption in most countries.

[6] 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.

[7] 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.

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

$$\sum_r \left(\sum_j q^E_{r,j} + q^I_r \right) = \overline{Q} = \sum_r \overline{Q}_r \tag{5}$$

where $\overline{Q}$ is the exogenous emissions cap, and $\overline{Q}_r$ is the exogenous number of allowances allocated to region r.[9] Let $\overline{Q}^{REF}$ 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.[10] 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.[11] We assume that the price tag is independent of whether emissions reductions take place domestically or abroad.[12]

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):

$$W_r = u^C_r\left(e^C_r\right) - \sum_j c^E_{r,j}\left(y^E_{r,j}\right) + p^I y^I_r - c^I_r\left(y^I_r, e^I_r, q^I_r\right) + p^Q\left(\overline{Q}_r - \sum_j q^E_{r,j} - q^I_r\right) + \tau_r\left(\overline{Q}^{REF} - \overline{Q}\right) \tag{6}$$

The full derivation is shown in Appendix A. The first term in (6) (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 valuation of emissions reductions.

Phasing out coal can also provide other environmental benefits such as reduced local air pollution. Here we assume that this negative externality is already fully internalized via market- or non-market-based instruments (and no spillover to other countries), in which case these environmental costs are implicitly covered by the cost functions. At the end of our numerical simulations, we return to this issue with a back-of-the-envelope calculation on additional welfare gains from reduced local air pollution (see section 3.4).

2.2. Effects of phasing out of coal power

2.2.1. No change in emissions cap

Assume now that (only) region 1 decides to phase out coal power ("coal phaseout"). 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 ($dy^E_{1,C} < 0$), 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.

Table 1 shows the sign of direction for the variables of key interest. We refer to Appendix A for a detailed derivation of these signs – here we just discuss our main 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 our numerical simulations based on empirical data they increase).

Next, we consider the effects on welfare in region r by a marginal reduction in coal power production in region 1 ($dy^E_{1,C} < 0$). By totally differentiating (6) (and using first order and equilibrium conditions) we get for region r:

$$dW_r = \left(c^{E\,\prime}_{r,C}\left(y^E_{r,C}\right) + \sigma_C p^Q - p^E_r\right)\left(-dy^E_{r,C}\right) + dp^Q\left(\overline{Q}_r - \sum_j q^E_{r,j} - q^I_r\right) \tag{7}$$

where the first term is zero for regions 2 and 3. Initially, when coal power generation is marginally reduced, the first parenthesis is zero (cf. the first order condition (12) in Appendix A). The last parenthesis is also zero if we consider three symmetric regions, in which case

[9] In the EU ETS, a large part of allowances is 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.

[10] 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).

[11] The price tag may be motivated by e.g. an assumed social cost of carbon (for the world or the region), or an assumed global carbon price consistent with the 1.5–2° target, or by other externalities that are not fully internalized such as technology spillovers or local air pollution, or by taking a lead role for a decarbonized economy, or simply by political economy pressures from lobby groups.

[12] 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
Effects of phasing out coal in region 1. Unchanged emissions cap.

	dp_r^E (electr. price)	dp^Q (quota price)	$dy_{r,C}^E$ (coal power prod.)	$dy_{r,G}^E$ (gas power prod.)	$dy_{r,R}^E$ (renew. power prod.)	dq_r^I (ind. emiss.)	$\sum_j q_{r,j}^E$ (electr. emiss.)	dQ_r (total emiss.)
Region 1	+	–	–	+	+	?	–	–
Region 2&3	–	–	+	?	–	+	+	+

there would be no initial net trade in emissions.[13] 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, not only due to reduced welfare in the domestic electricity market but also due to terms-of-trade losses in the allowance market.

If region 1 is initially a net importer of emissions quotas ($Q_r > \overline{Q}_r$), the last term in (7) 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 is welfare enhancing for region 1 if the region is a net importer of quotas.

In the symmetric case, welfare effects for regions 2 and 3 are positive, 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, emphasizing the importance of terms-of-trade effects in the allowance market:

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.*

2.2.2. 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 how 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: $d\overline{Q}_1 = \omega^U \sigma_C dy_{1,C}^E < 0$, 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: $d\overline{Q} = \omega^A(\sigma_C dy_{1,C}^E) < 0$ with $0 < \omega^A \leq 1$ and $d\overline{Q}_r = (\overline{Q}_r/\overline{Q})d\overline{Q}$. 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 (we return to the MSR in the numerical simulations).

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, and 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 prices (cf. Appendix A). If higher emissions from gas power production dominate lower industry emissions *at the initial quota price*, the quota price will increase (and vice versa). If the quota price drops ("Alternative 1"), we get the same qualitative results as without any change in the emissions cap (see Table 1), but 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.

The welfare effects are slightly changed since total emissions are no longer fixed. In the case with unilateral cancellation, we get the following expression for region *r*:

$$dW_r = \left(c_{r,C}^{E\,\prime}\left(y_{r,C}^E\right) + \sigma_C p^Q - p_r^E\right)\left(-dy_{rC}^E\right) + dp^Q\left(\overline{Q}_r - \sum_j q_{r,j}^E - q_r^I\right) + \omega^U \sigma_C\left(\left(-dy_{1C}^E\right)\tau_1 - \left(-dy_{rC}^E\right)p^Q\right) \tag{8}$$

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

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

	dp_r^E (electr. price)	dp^Q (quota price)	$dy_{r,C}^E$ (coal power prod.)	$dy_{r,G}^E$ (gas power prod.)	$dy_{r,R}^E$ (renew. power prod.)	dq_r^I (ind. emiss.)	$\sum_j q_{r,j}^E$ (electr. emiss.)	dQ_r (total emiss.)
Region 1	+	+	–	+	+	–	–	–
Region 2&3	+	+	–	?	+	–	–	–

[a] Alternative 1 (lower quota price) has the same signs as in Table 1.

where again the first term is zero for regions 2 and 3. Note that there is an additional term 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.[14] 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 initially profitable coal power generation. The size of the second term in (8) is still negative (see above), but most likely smaller in size than in (7), since the quota price changes less.[15]

The marginal welfare impacts of gradually phasing out coal combined with unilateral cancellation of allowances can be illustrated in Fig. 1. Four alternatives are shown, where three of them assume the marginal welfare effects of a small reduction in coal power production to be positive (e.g., symmetric regions and $\tau_1 > p^Q$). In the fourth case ("Initial loss"), 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 (total welfare effects are given by the area between the line and the x-axis). 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.

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 (8)). 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 (8) will still be positive if and only if $\tau_1 > p^Q$, but the size of the two first terms in (7) and (8) 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 (8)) 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 quota cancellation if the price tag on emissions is at least as high as the ETS price (see our numerical 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*:

[14] 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).

[15] 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 $\tau_1 > p^Q$.

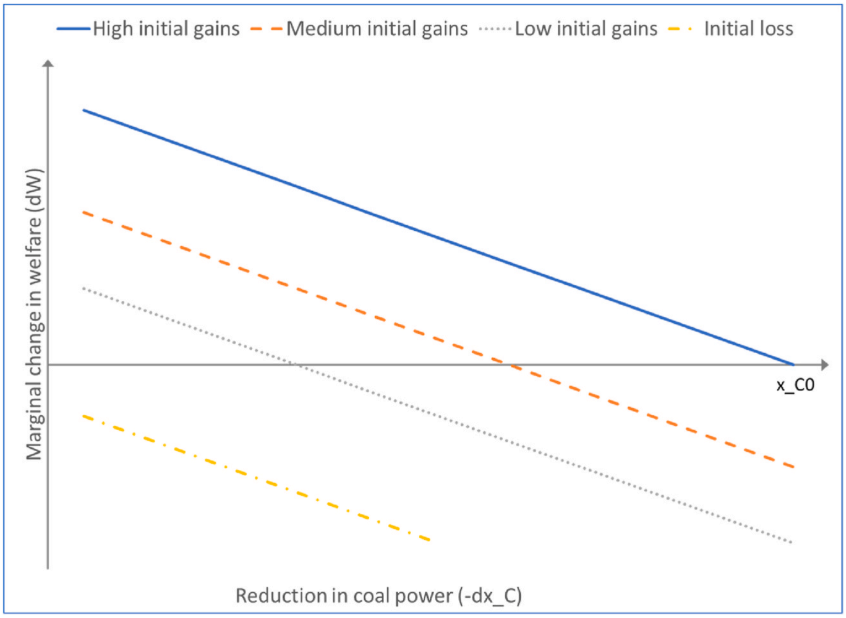

Fig. 1. Marginal welfare effects in region 1 of gradually phasing out coal power production in region 1, combined with unilateral cancellation of allowances. Illustration of four different cases.

- *If the regions are symmetric, 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:

$$dW_r = \left(c^{E\,\prime}_{r,C}\left(y^E_{r,C}\right) + \sigma_C p^Q - p^E_r\right)\left(-dy^E_{rC}\right) + dp^Q\left(\overline{Q}_r - \sum_j q^E_{r,j} - q^I_r\right) + \omega^A \sigma_C\left(-dy^E_{1C}\right)\left(\tau_r - \frac{\overline{Q}_r}{\overline{\overline{Q}}}p^Q\right) \tag{9}$$

The last term in (9) is more likely to be positive than the last term in (8), 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 (8) may be bigger than (9). 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 which regulates 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.*

2.2.3. 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 region *r* are still given by equation (7). 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 (7) can go either up or down.

With unilateral cancellation by the two regions (and equal ω^U), the welfare effects for region *r* are given by a slightly modified Eq. (8):

$$dW_r = \left(c_{r,C}^{E\ \prime}\left(y_{r,C}^E\right) + \sigma_C p^Q - p_r^E\right)\left(-dy_{rC}^E\right) + dp^Q\left(\overline{Q}_r - \sum_j q_{r,j}^E - q_r^I\right) + \omega^U \sigma_C\left(\left(\sum_{k=1}^{2} -dy_{kC}^E\right)\tau_r - \left(-dy_{rC}^E\right)p^Q\right) \tag{10}$$

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 of emissions reduction is $\sum_r \tau_r > p^Q$.[16] 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 (8) and (10) are zero, while the last term is biggest in (10). 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 terms in (8) and (10) do not change, and hence region 1's welfare becomes unambiguously more positive or less negative.

With joint cancellation, the welfare effects for region *r* become:

$$dW_r = \left(c_{r,C}^{E\ \prime}\left(y_{r,C}^E\right) + \sigma_C p^Q - p_r^E\right)\left(-dy_{rC}^E\right) + dp^Q\left(\overline{Q}_r - \sum_j q_{r,j}^E - q_r^I\right) + \omega^A \sigma_C\left(\sum_{k=1}^{2} -dy_{kC}^E\right)\left(\tau_r - \frac{\overline{Q}_r}{\overline{Q}}p^Q\right) \tag{11}$$

The only difference compared to (9) (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 which regulates 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 fundamental qualitative economic and emissions 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.

[16] 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 could be that each country only values the emissions reductions following from its own actions.

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,[17] and focus 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 (fuel costs include CO_2 prices), and materials with technology-specific resources (capital and natural resources such as water, sun, wind, or 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). As electricity produced with different technologies are perfect substitutes, output from different electricity technologies is treated as a homogeneous good within each region, entering 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.[18]

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; 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 CO_2 emissions for 40 regions and 31 sectors covering the world economy.[19] 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.[20] 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 CO_2 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.

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.

3.2. Policy scenarios

In our policy scenarios, we focus on 2030 as the prominent near-by 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 CO_2 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 CO_2, to comply with the more stringent emissions cap.[21]

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

[18] We do not model transmission capacities explicitly but control the magnitude of cross-country electricity trade by the choice of Armington elasticities.

[19] As a starting point, the JRC dataset builds upon the GTAP database which in its latest version (GTAP10) covers 141 regions and 65 sectors of the global economy for the base-year 2014 (Aguiar et al., 2019).

[20] 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).

[21] In the Non-ETS segments of the EU countries, national CO_2 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 CO_2 prices are adjusted endogenously to meet the exogenous national Non-ETS targets.

Table 3
Sectors and regions in the CGE model.

Sectors and commodities[a]	Countries and regions[b]
Primary energy sectors	*EU countries/regions*
Coal	Germany (DEU)
Crude Oil	United Kingdom + Ireland (GBR)
Natural Gas	France (FRA)
Emission-intensive and trade-exposed sectors	Poland (POL)
Chemical Products	Spain + Portugal (SPP)
Non-Metallic Minerals	Italy + Malta (ITA)
Iron and Steel	Greece + Cyprus (GRE)
Non-Ferrous Metals	Belgium + Netherlands + Luxemburg (BNL)
Refined Oil	Sweden + Denmark + Finland (SCA)
Paper Products, Publishing	Bulgaria + Romania (SEU)
Air Transport	Estonia + Latvia + Lithuania (BAL)
Electricity generation and distribution	Central European countries (CEU)[c]
Coal-fired	*Non-EU countries/regions*
Oil-fired	Rest of Europe and Turkey (RET)
Gas-fired	United States of America (USA)
Nuclear	China (CHN)
Biomass	Russia (RUS)
Hydroelectric	Rest of the World (ROW)
Wind power	
Photovoltaics	
Transmission and distribution	
Other sectors	
Services	
All other goods	

[a] All sectors except Transmission and distribution, Services and All other goods are regulated by the EU ETS.
[b] Acronyms which we use later in our exposition of simulation results are provided in brackets).
[c] CEU includes Austria, Czech Republic, Slovakia, Hungary, Slovenia, and Croatia.

Table 4
Coal phaseout scenarios for 2030.

		Cancellation of allowances		
		None	Unilateral	Centralized via MSR
Regional coverage	Unilateral	*UNI*	*UNI-UC*	*UNI-MSR*
	Coalition	*COA*	*COA-UC*	*COA-MSR*

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*).

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 the *REF* scenario for 2030).[22] 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 (Poland) and SEU (Bulgaria and Romania), based on information about coal phaseout decisions or similar considerations (Agora Energiewende and Sandbag, 2020).[23]

Cancellation of allowances (if any) follows the setup in the analytical model. We consider 100% cancellation ($\omega^U = 1$ and $\omega^A = 1$), meaning that cancellation of allowances by the coal phaseout region(s) is equal to the emissions from the phased out coal power

[22] In 2018, Germany's share of coal power generation in the EU was slightly above one third (BP, 2019), while in our *REF* scenario for 2030 it is around one half.

[23] 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 Poland, Romania, and Bulgaria 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 small in terms of (coal) power production.

generation, but we also report the effects of 50% cancellation.[24] Instead of choosing specific price tags on emissions ourselves (i.e., valuations per ton emissions reductions, cf. discussion leading up to equation (6), including footnote 11), 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 (see Appendix B for details).[25]

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.

3.3.1. Unilateral coal phaseout in Germany

In the *REF* scenario with an EU ETS price of 47 Euro per ton CO_2, 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 – these reductions amount to around 10% of EU ETS emissions).

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 electricity sector emissions in the ETS emissions 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 slightly drop due to the higher ETS price.[26] 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. Fig. 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

[24] 100% cancellation via the MSR may seem overly optimistic but is included to ease the comparison with unilateral cancellation. We return to this issue below.

[25] 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.

[26] There are a few slight deviations from the analytical findings in Tables 1 and 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).

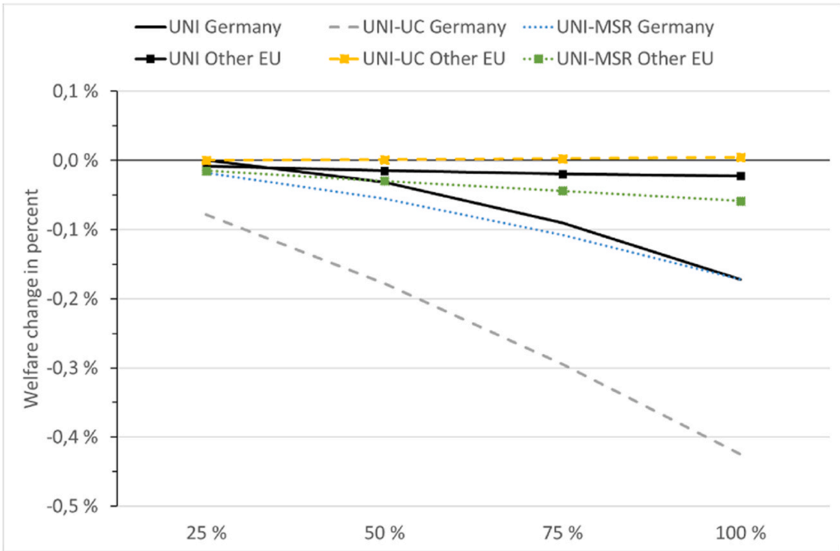

Fig. 2. Welfare effects of coal phaseout for Germany and the rest of the EU in *UNI*, *UNI-UC* and *UNI-MSR* scenarios (% from *REF*) without emissions valuation.

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). The 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 Eq. (8)). 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.

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.[27] For the composite of other EU countries, we see from Fig. 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.

The main motivation behind phasing out coal is the cutback of CO_2 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 CO_2 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 CO_2 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 Fig. 3 the welfare effects for Germany as a function of the country's valuation of emissions reductions under complete phaseout. The welfare effects on the y-axis correspond to the numbers reported in Fig. 2 (e.g., the almost −4 billion Euro in *UNI-100%* in Fig. 3 corresponds to the −0.17% at the right end of *UNI Germany* in Fig. 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.

[27] 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).

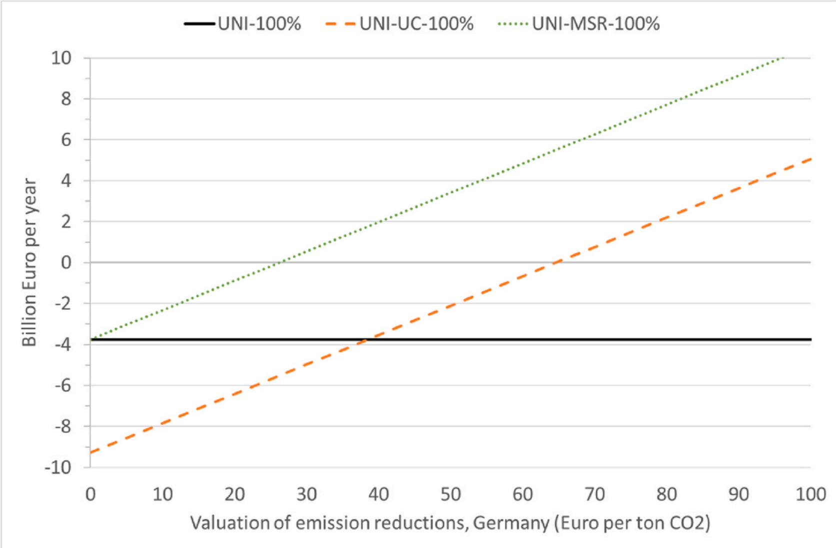

Fig. 3. Welfare effects of coal phaseout in Germany in *UNI*, *UNI-UC* and *UNI-MSR* scenarios as a function of valuation of emissions reductions (% from *REF*).

First, we notice that *given a decision to phase out coal*, unilateral cancellation of allowances is welfare-improving for Germany if the country values CO_2 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.

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 CO_2 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 Fig. 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,[28] while complete phaseout is the optimal choice if the price tag is 83 Euro per ton or higher.[29]

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 Fig. 3. 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).

As indicated before, 100% cancellation of allowances via the MSR may not be realistic. Perino (2018) suggests that one additional ton of emissions reduction in 2020 reduces the long-term emissions cap by 0.4–0.8 tons (via the MSR), i.e., a cancellation rate of 40–80%. Gerlagh et al. (2021) find that the long-term cap is reduced by 0.9 tons (i.e., a cancellation rate of 90%) if the reduction takes place in 2020 while the cancellation rate may turn negative if the reduction takes place a couple of decades later but is announced already now (see also Rosendahl, 2019). Thus, it is difficult to predict how effective the MSR will be in killing allowances, and we have

[28] 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. Fig. 2), without cancellation a limited phaseout is optimal even though emissions remain unchanged. The optimal phaseout rate is then 15%, and this will be the best solution for Germany for price tags below 49 Euro per ton. For higher price tags, phaseout combined with cancellation is the best choice.

[29] As mentioned before, we do not want to enter into a discussion about the appropriate valuation of emission reductions. Estimates of the social cost of carbon vary significantly, and there are methodologically difficulties involved in such calculations (see e.g. Pindyck, 2013). As mentioned above though, the German Environmental Agency (UBA, 2020) has proposed using 215 Euro per ton CO_2 (in 2030) when evaluating the damages of CO_2 emissions for public planning.

run a number of simulations where we vary the cancellation rate ω^A between 0% and 100%. The results are shown in Figure C2 in Appendix C, where we focus on the price tag to make coal phaseout welfare-improving for Germany.[30] If the cancellation rate via the MSR drops from 100% to 50%, the required price tag on emissions increases from 27 to 51 Euro per ton, while if the cancellation rate is merely 20%, the required price tag becomes 128.

It is also worth mentioning here that the two types of cancellation, i.e., unilateral cancellation and cancellation via the MSR mechanism, may interact. Gerlagh and Heijmans (2019) find that unilateral cancellation (e.g., along with coal phaseout) may be undermined by the MSR, as fewer allowances then become cancelled via the MSR.

3.3.2. 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 Fig. 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 – Italy (ITA) and the composite region of Greece and Cyprus (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.

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.

3.3.3. 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 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, Fig. 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 Fig. 5 correspond to the blue dots in Fig. 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.[31] 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 C3 in Appendix C we plot the welfare difference between *COA* and *UNI* versus the initial net export of allowances (as a share of emissions), showing a clear negative relationship.[32] 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).

[30] If the cancellation rate via the MSR is negative ($\omega^A < 0$), cumulative emissions are increased instead of decreased as a result of the coal phaseout. Then the required price tag must be negative in order to make the phaseout welfare-improving unless there are other benefits not covered by our analysis (e.g., reduced local air pollution, cf. the discussion in section 3.4).

[31] 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.

[32] 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.

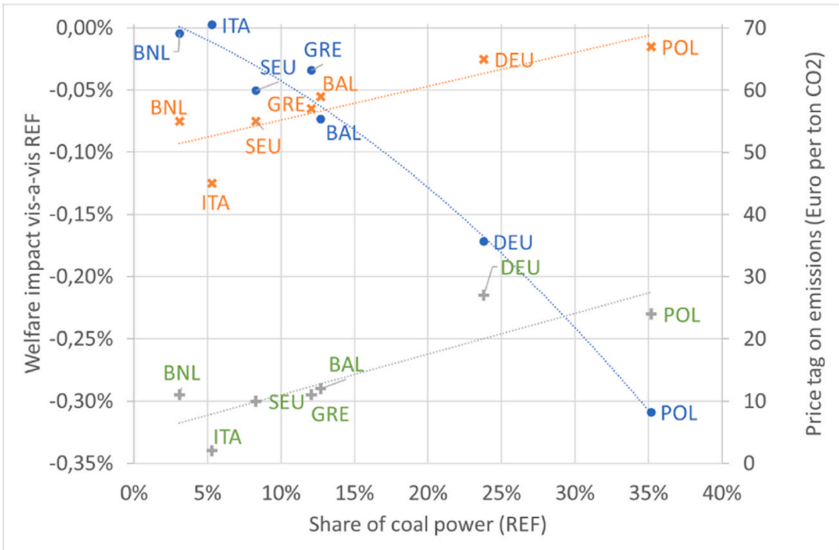

Fig. 4. Welfare effects of coal phaseout in different EU regions in *UNI* scenario, and required price tag on emissions in *UNI-UC* and *UNI-MSR* scenarios*. * The blue dots show welfare impacts in the *UNI* scenarios (left axis), the red x's show the required price tag on emissions in the *UNI-UC* scenarios (right axis), while the green +'s show the required price tag on emissions in the *UNI-MSR* scenarios (right axis).. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

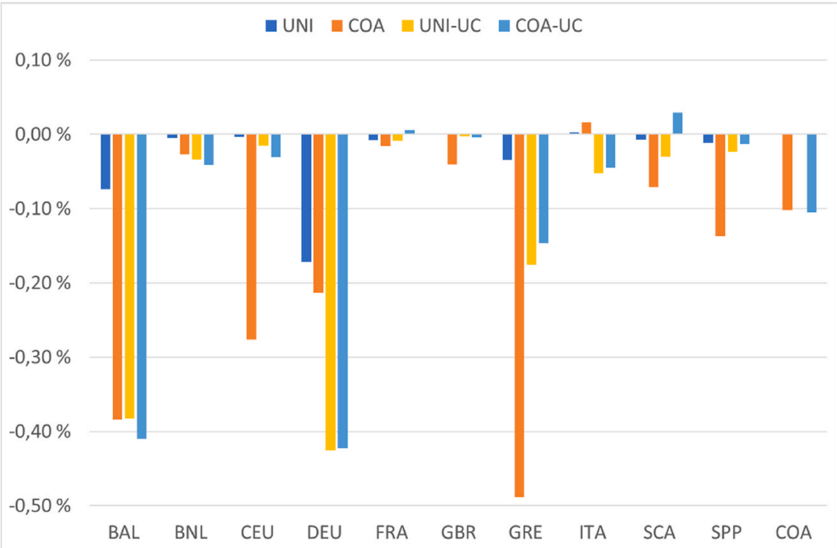

Fig. 5. Welfare effects of unilateral and multilateral coal phaseout. Percent change vis-a-vis *REF**. * Valuation of emissions reductions is disregarded.

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. For the coalition as a whole, welfare effects are almost unchanged by the cancellation.

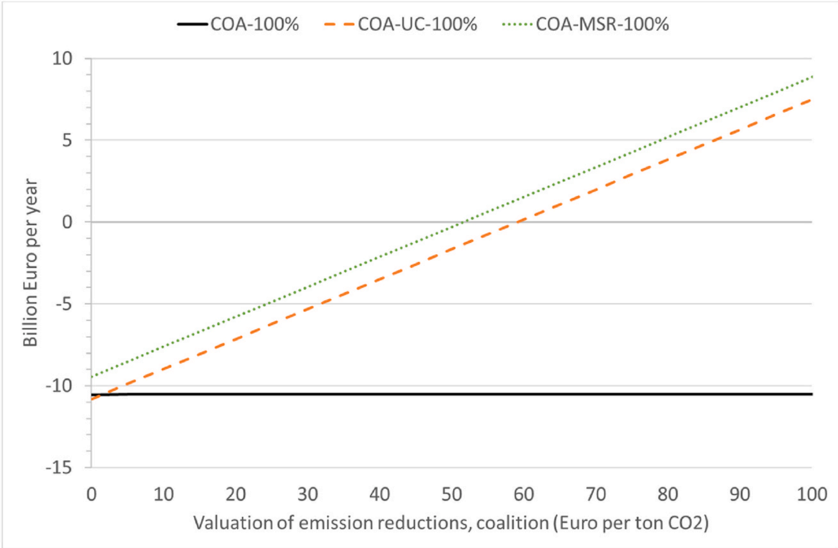

Fig. 6. Welfare effects of coal phaseout in the coalition in *COA*, *COA-UC* and *COA-MSR* scenarios. Percent change vis-a-vis *REF*.

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 CO_2 emissions, see Fig. 6. There are several differences vis-à-vis the corresponding Fig. 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.

3.4. Sensitivity analysis

We present sensitivity analysis with respect to key parameters 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 (the *BMK* scenario is consistent with EU's initial Paris target of 40% reduction vis-à-vis 1990). Here we set the *REF* cap equal to respectively the *BMK* cap, and 31.6% below the *BMK* cap. The latter is based on the Fit-for-55 proposal from the European Commission (2021).[33] 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 Fig. 4, except that we skip the MSR scenario). At the end of this section, we also present some rough calculations of benefits from reduced air pollution due to coal phaseout in Germany.

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 CO_2 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

[33] The European Commission (2021) states that "-61% compared to 2005 … is taken as the EU ETS ambition contributing to an overall target of at least −55% compared to 1990". The *BMK* scenario is based on the previous EU-wide target of −40%, with «43% reduction in EU ETS emissions by 2030 compared to 2005». Thus: (1-(1-0.61)/(1-0.43)) = 0.316.

Table 5
Sensitivity analysis for unilateral coal phaseout in Germany[a].

	ETS-price in *REF* (Euro per ton CO_2)	Welfare effect *UNI* (vis-à-vis *REF*)	Price tag *UNI-UC* (Euro per ton CO_2)
Main simulation	**47**	**−0,17%**	**65**
Lower supply elasticities	62	−0,27%	94
Higher supply elasticities	32	−0,14%	49
Lower trade elasticities	47	−0,14%	62
Higher trade elasticities	45	−0,21%	69
Tighter emissions cap	85	−0,01%	85
Weaker emissions cap	32	−0,28%	56

[a] Lower and higher elasticities mean respectively 50% lower and 100% higher elasticities as compared to our central case parameterization. Tighter emissions cap means 31.6% below the *BMK* scenario value, while weaker cap means exactly the value of the *BMK* scenario.

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.

If the emissions cap is tighter ("Fit-for-55"), welfare costs are close to zero as the initial share of coal power in the *REF* scenario is already low (9% versus 24% in the main simulation) and the remaining coal power (before phaseout) is less profitable due to much higher ETS price. With weaker 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 weaker emissions cap, much more emissions allowances are cancelled and hence the emissions reductions are much bigger.

Finally, in our simulations we have disregarded potential benefits from reduced local air pollution related to coal phaseout. To assess such benefits explicitly, one requires estimates of external air pollution costs across power generation technologies, which depend on the location of power plants, emission factors for different pollutants (which vary across plants), assessments of exposed populations, health impacts, etc. The German Environment Agency (Bünger and Matthey, 2020) provides air pollution costs of different electricity generation technologies, reporting 1.68 Eurocent per kWh for hard coal and 2.05 for lignite. If we apply an average of these two figures, and combine it with the German coal power generation in the *REF* scenario (213 TWh), we obtain a value of reduced air pollution corresponding to 4 billion Euro. This is a significant potential gain, and in fact almost identical to the German welfare cost found above when disregarding gains from reduced air pollution (*UNI* scenario).[34]

If we account for increased German gas and bio power generation (in the *UNI* scenario), the net value is reduced to 3.8 billion (the small difference is due to a limited expansion of gas and bio power and lower external costs of gas than coal power). If we had accounted for the fact that air pollution is regional and not only local, meaning that air pollutants cross borders, the net value would probably decline more, both because parts of the gain of 4 billion Euro would accrue to neighboring countries and because of increased coal power generation in these neighboring countries. The latter effect would be much smaller though if emissions allowances are cancelled, in which case coal power generation outside Germany is almost unchanged. The same holds if most EU member states phase out coal jointly.

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.

The aim of this paper has been to shed some light into the pros and cons of premature phaseout of coal power. We have examined theoretically and numerically the consequences of this, both for the electricity markets, countries' economic welfare, and CO_2 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

[34] Samadi (2017) presents life cycle air pollution costs per kWh of state-of-the-art electricity generation technologies in Europe. These cost figures are about 1/3 lower than those reported by the German Environment Agency. Applying these figures instead, the net gain from reduced air pollution costs are reduced from 3.8 to 2.4 billion Euro.

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 a coalition of EU countries phase out coal jointly and do not cancel allowances, we find that most of them 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. With cancellation, however, around half of the countries are better off than when acting unilaterally. For the coalition as a whole, coal phaseout with cancellation is welfare-improving (compared to no phaseout) if the price tag is at least 60 Euro per ton.

Given that the motivation for phasing out coal is to reduce CO_2 emissions, and emissions reductions are only achieved if allowances are canceled, one may ask why not simply cancel allowances without a politically determined coal phaseout. That is, let the CO_2 price work alone. If Germany were to choose such a policy, i.e., unilaterally cancel allowances corresponding to the CO_2 emissions from coal power generation in the reference scenario, the German welfare costs would be almost as high as when the country combines coal phaseout with allowance cancellation (the cost difference is merely 5%). The main reason for the small difference is that the ETS price increases from 47 to 61 Euro per ton under cancellation without phaseout, and Germany becoming a much bigger importer of emissions allowances.

Phasing out coal can have different motivations though, as touched upon before. In our paper, we have focused on the impacts on CO_2 emissions in addition to economic welfare effects. Phasing out coal can also reduce emissions of other local and regional pollutants such as NOx, SO2 and particles, and hence reduce the health and environmental damages from such pollution (Rauner et al., 2020). As shown in the previous section, accounting for these benefits might be significant compared with the costs of phasing out coal power. Moreover, we have not taken into account possible long-term and indirect effects on CO_2 emissions via speeding up the transition to CO_2 free energy and technology (see e.g. Rozenberg et al., 2020), which might reduce the costs of reaching long-term targets. For instance, Goulder (2020) is concerned about speeding up CO_2 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 CO_2 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. 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., 2020a). 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.

Both our theoretical and numerical analyses are static and deterministic, reflecting medium-to long-run equilibrium effects. As stated in the discussion of the MSR in Section 3.3, the functioning of the EU ETS is dynamic, and this is especially important when it comes to cancellation via the MSR. Announcing coal phaseout many years ahead (which we implicitly assume) not only gives power producers time to adjust their production capacities, but also affects the extent of allowance cancellation via the MSR. As shown e.g. by Gerlagh et al. (2021), however, cancellation via the MSR is bigger if coal phaseout (or other supplementary policies) is *not* anticipated compared to if it is announced well in advance. Hence, if cancellation of emissions allowances is important for the policy makers, reducing the time lag between announcement and implementation may be desirable.

On the other hand, a short time lag increases the likelihood of stranded assets for coal power plants, especially if plants are built or upgraded shortly before the phaseout is implemented. Then the welfare costs of coal phaseout would likely be higher than our numerical results suggest. An upper limit of these stranded assets is indicated by the rents accruing to coal power generators in our reference scenario, which in Germany are around 2 billion Euro per year. This amounts to 55% of the annual welfare loss calculated for Germany in the scenario without cancellation. As the German coal phaseout will take place rather gradually (end by 2038), the stranded assets will probably be much smaller. A political decision to phase out coal may also reduce the uncertainty for power market participants, especially considering the huge (and apparently not foreseen) increase in the EU ETS price since 2017.

Coal phaseout is on the agenda not only in Europe, but in several other (mainly OECD) countries, too (Littlecott and Webb, 2017). Moreover, in the Glasgow Climate Pact (COP26), all Parties to the Paris Agreement agreed to at least "phasing down" of coal (Vaughan, 2021). 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 focus in our paper.

Declaration of competing interest

None.

Acknowledgement

We acknowledge funding from The Research Council of Norway through the NorENS project (grant 280987) and from the German Federal Ministry of Education and Research through the CarPri project (grant 01LA1816B).

Appendix A. Analytical derivations

First order conditions

Here we first show the first order conditions (always assuming interior solution). The first order condition for electricity producers is:

$$p_r^E = c_{r,j}^{E\,\prime}\left(y_{r,j}^E\right) + \sigma_j p^Q \tag{12}$$

The first order conditions for industry sector producers are:

$$p^I = \partial c_r^I\left(y_r^I, e_r^I, q_r^I\right) / \partial y_r^I \tag{13}$$

$$p_r^E = -\,\partial c_r^I\left(y_r^I, e_r^I, q_r^I\right) / \partial e_r^I \tag{14}$$

$$p^Q = -\,\partial c_r^I\left(y_r^I, e_r^I, q_r^I\right) / \partial q_r^I \tag{15}$$

The first order condition for consumers is:

$$p_r^E = u_r^{C'}\left(e_r^C\right) \tag{16}$$

The derivation of W_r in (6) is as follows:

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

Next, 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 (12) we get the changes for electricity producers:

$$dp_r^E = c_{r,j}^{E\,\prime\prime}\left(y_{r,j}^E\right) dy_{r,j}^E + \sigma_j dp^Q \tag{17}$$

From (13)-(15) we get the changes for the industry producers:

$$\partial^2 c_r^I / \partial y_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial y_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial y_r^I \partial q_r^I \cdot dq_r^I = 0 \tag{18}$$

$$\partial^2 c_r^I / \partial e_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial e_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial e_r^I \partial q_r^I \cdot dq_r^I = dp_r^E \tag{19}$$

$$\partial^2 c_r^I / \partial q_r^I \partial y_r^I \cdot dy_r^I + \partial^2 c_r^I / \partial q_r^I \partial e_r^I \cdot de_r^I + \partial^2 c_r^I / \partial q_r^I \partial e_r^I \cdot dq_r^I = dp^Q \tag{20}$$

From (16) and (4)-(5) we get the changes for the consumers, as well as the changes in the electricity and quota markets, respectively:

$$dp_r^E = u_r^{C''}\left(e_r^C\right)de_r^C \tag{21}$$

$$\sum_j dy_{r,j}^E = de_r^I + de_r^C \tag{22}$$

$$\sum_r \left(\sum_j dq_{r,j}^E + dq_r^I\right) = \sum_r dQ_r = 0 \tag{23}$$

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. (22)), the domestic electricity price must increase: $dp_1^E > 0$. From (19) and (21) we then get $de_1^I < 0$ and $de_1^C < 0$,[35] while from (17) 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. (18) and (20)).[36] 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 (23), and hence the quota price drops, $dp^Q < 0$.

In country 1, this has second-order effects as follows: Gas power production increases its production (and emissions) further, cf. (17), 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. (20)) 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. (17)), 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. (17)) – hence we cannot say whether gas power production in countries 2 and 3 increases or decreases. Renewable power production will fall (cf. (17)), while from (19) and (21) 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, $d\overline{Q}_1 = \sigma_C(dy_{1C}^E) < 0$. 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. Sector-specific and technology-specific energy resources are tied to technologies and sectors in each region.

All commodities except for fossil fuels and technology-specific electricity are produced according to a four-level nested constant-

[35] We here assume that the direct price effect in dominates any indirect effects via changes in output and/or emissions caused by the electricity price increase.

[36] Remember that the cross-derivatives are assumed to be negative. Hence, the second terms in and 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 $dy_1^I < 0$.

elasticity-of-substitution (CES) cost function combining inputs of capital (K), labor (L), energy (E), and material (M) – see Figure B1. 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. On the output side, domestic production is split subject to a constant-elasticity-of-transformation (CET) function between export supply to foreign markets and domestic supply to the home market.

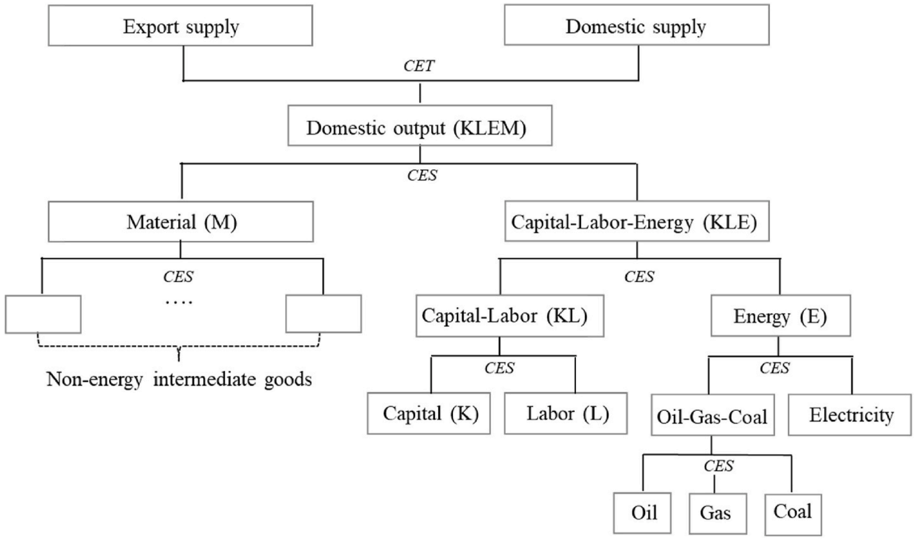

Fig. B1. Production structure for representative industry

Fossil fuel production is represented by a 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 embodied in power plants 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.[37] 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 quite 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.

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.[38] A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of coal, refined oil and natural gas, with CO_2 coefficients differentiated by fuels and sector of use. Restrictions to the use of CO_2 emissions in production and consumption are implemented through explicit emissions pricing of the carbon associated with fuel combustion either via CO_2 taxes or the auctioning of CO_2 emissions allowances.

[37] 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).

[38] We do not model transmission capacities explicitly. However, even with high Armington elasticities for electricity trade between EU regions, trade is limited by the initial trade volumes due to the underlying CES structure.

CO_2 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	3
Oil-fired	1
Gas-fired	3
Nuclear	0
Biomass	2
Hydroelectric	0.5
Wind power	2
Photovoltaics	2

Table B2
Share of auctioned allowances per country participating in the EU ETS

Austria	1.4%
Belgium	2.2%
Bulgaria	1.9%
Croatia	0.7%
Cyprus	0.4%
Czech Republic	4.5%
Denmark	1.1%
Estonia	0.7%
Finland	1.6%
France	5.2%
Germany	20.8%
Great Britain	10.9%
Greece	4.2%
Hungary	1.8%
Iceland	0.0%
Ireland	0.8%
Italy	8.9%
Latvia	0.3%
Liechtenstein	0.0%
Lithuania	0.5%
Luxembourg	0.1%
Malta	0.1%
Netherlands	3.7%
Norway	0.9%
Poland	11.9%
Portugal	2.4%
Romania	3.4%
Slovakia	1.5%
Slovenia	0.6%
Spain	6.4%
Sweden	0.9%

Source: Own calculations based on data for verified emissions and GDP per capita. For details about the rules, see https://ec.europa.eu/clima/policies/ets/auctioning_en#tab-0-2

Appendix C. Numerical results – additional figures

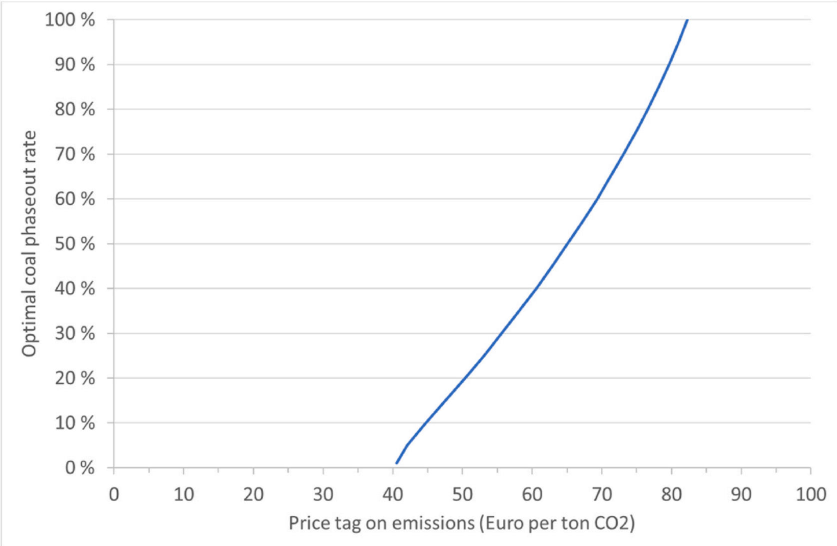

Fig. C1. Optimal coal phaseout rate in Germany in the *UNI-UC* scenario as a function of Germany's price tag on emissions

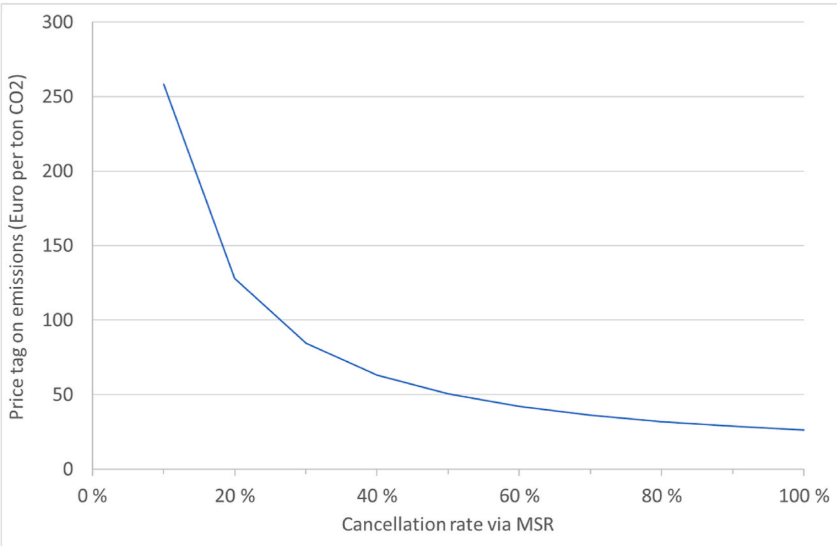

Fig. C2. Price tag on emissions in Germany under different assumptions about the cancellation rate via the MSR

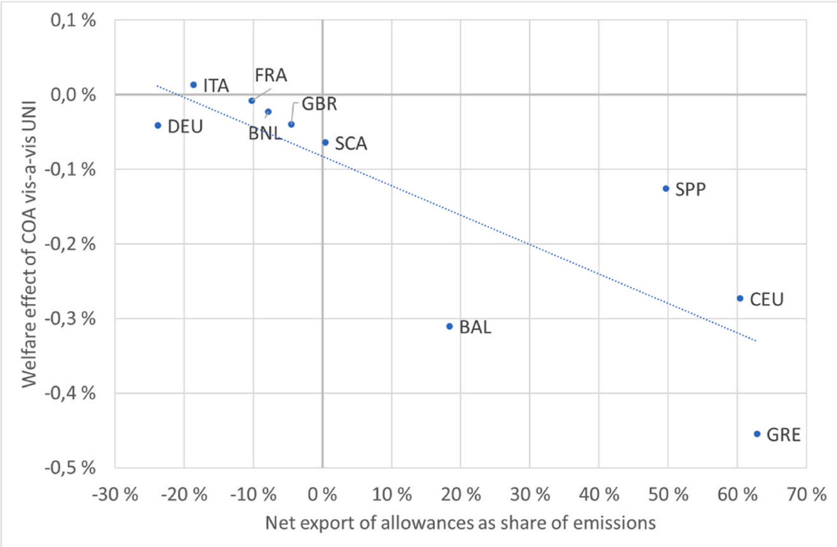

Fig. C3. Plot of net export of allowances as share of emissions in the *REF* scenario versus welfare effects of the *COA* scenario relative to the *UNI* scenario for coalition regions

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