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Abstract

Using the dynamic, three-region environmental multi-sector general equilibrium model EMuSe, we find that pricing carbon in Germany or Spain only leads to a permanent negative effect on output in these economies. The induced emissions reduction is not large enough to overcompensate for the increase in marginal production costs. If the rest of Europe joins the carbon pricing scheme, long-run output effects are positive. However, in this case, transition costs are even larger due to close trade relations within Europe. We find evidence for carbon leakage, which can be reduced slightly by a border adjustment mechanism. Still, it is no game changer as it mainly protects dirty domestic sectors. While Germany benefits from border adjustment, Spain actually loses throughout the transition. In the long run, the Spanish energy sector benefits most because of its relatively low emission intensity. Finally, Europe has a strong incentive to get the rest of the world on board as then the downturn is shorter and long-run benefits are larger.

Keywords: carbon pricing, border adjustment, climate clubs, international dynamic general equilibrium model, sectoral heterogeneity, input-output matrix.

JEL classification: E32, E62, F42, H32, Q58.

Resumen

Utilizando el modelo dinámico de equilibrio general multisectorial medioambiental de tres regiones EMuSe, encontramos que una tarificación del carbono limitada a Alemania o España solo conduce a un efecto negativo permanente sobre la producción en estas economías. La reducción de emisiones que ello provoca no es lo suficientemente grande como para compensar el aumento de los costes marginales de producción. Si el resto de Europa se adhiere al sistema de tarificación del carbono, los efectos a largo plazo sobre la producción serán positivos. Sin embargo, en este caso, los costes de transición serían aún mayores debido a las estrechas relaciones comerciales dentro de Europa. Encontramos evidencias que apuntan a la fuga de carbono, la cual puede reducirse ligeramente mediante un mecanismo de ajuste en frontera. Aun así, este mecanismo no cambia las reglas del juego, ya que protege principalmente a los sectores nacionales contaminantes. Mientras que Alemania se beneficia del ajuste fronterizo, España sale perdiendo durante la transición, aunque a la larga el sector energético español será el más beneficiado por su relativamente baja intensidad de emisiones. Por último, Europa cuenta con un gran incentivo para que el resto del mundo se sume a la iniciativa, ya que así la recesión será más breve y los beneficios a largo plazo serán mayores.

Palabras clave: tarificación del carbón, ajuste en frontera, clubes climáticos, modelo internacional de equilibrio general dinámico, heterogeneidad sectorial, matriz *input-output.*

Códigos JEL: E32, E62, F42, H32, Q58.

1. Introduction

At the Paris summit in 2015, almost 200 nations (including Germany and Spain) agreed upon ambitious climate goals. Mitigation policies that are currently discussed at the European and G7/G20 level center around pricing carbon emissions. However, there is also the fear of carbon leakage, describing a situation in which production is shifted towards economies with less stringent climate policies. To address carbon leakage, border adjustment mechanisms and the formation of climate clubs range high on the political agenda. The assessment of the macroeconomic and environmental effects of these policies is of utmost importance.

This paper analyzes different climate policy scenarios and contrasts their consequences for Germany and Spain. More precisely, it mirrors the setup of Ernst et al. (2023) to study the effects of carbon pricing and border adjustment on these economies. For this purpose, it relies on the same three-region version of the **e**nvironmental **mu**lti-**se**ctor dynamic general equilibrium model *EMuSe*, but uses different calibrations. We apply the related *EMuSe* Calibration Toolkit to parameterize the model once for Germany, the rest of Europe and the rest of the world, and once for Spain with the same counterparts.[1]

The model captures input-output relationships between sectors as well as varying factor intensities, contributions to final demand and emission intensities across sectors along the lines of Bouakez et al. (2023). Moreover, it includes international trade of goods and assets. The environmental module follows the existing literature (e.g. Heutel, 2012, Annicchiarico and Di Dio, 2015 and Annicchiarico et al., 2018) by assuming that emissions are a by-product of production. Firms decide on abatement effort, which is costly. The world-wide stock of emissions leads to a productivity loss given by a damage function (see also Annicchiarico et al., 2022, for a discussion).

Our results can be summarized as follows. First, we confirm the general results of Ernst et al. (2023). Specifically, the introduction of a carbon price has a long-lasting negative effect on output as it increases marginal production costs. This might be overcompensated for if the emissions reduction and the corresponding productivity enhancing effect is large enough, i.e. if the group countries participating is large enough. Moreover, border adjustment helps to reduce carbon leakage, but the additional emissions reduction is rather limited. Additionally, our results support the view that Europe has a strong incentive to get the rest of the world on board.

However, we also add new insights because of the different composition of regions. Ernst et al. (2023) find that regions introducing carbon pricing always benefit by others joining them. While this holds true given their calibration for Europe, North America and the rest of the world, it might differ when modelling smaller subregions individually. Indeed, both Germany and Spain face additional output losses along the transition when the rest of Europe also introduces carbon pricing. In this case, the positive effects of a lager reduction in emissions-induced damage only pay off in the long run.

Comparing both countries directly, we find the following. First, Spain is slightly less affected directly by carbon pricing because its emission intensity is lower on average. Second, interestingly, we find opposite effects of the border adjustment across both countries. While Germany benefits from a border adjustment mechanism (relatively to carbon pricing without border adjustment), it actually reduces aggregate output in Spain during the transition period. This is because Germany exports more to the rest of the world, while Spain is more exposed to imports from the dirtiest sectors of the rest of

[1] See also Hinterlang et al. (2023a) for a technical documentation on EMuSe and its Calibration Toolkit.

the world. Still, the energy composite sector and the combined water and air transport sector in Spain benefit most from a European climate club. While the former mainly gains due to its relatively small emission intensity compared to the respective sectors in other regions, the latter benefits by increased European demand.

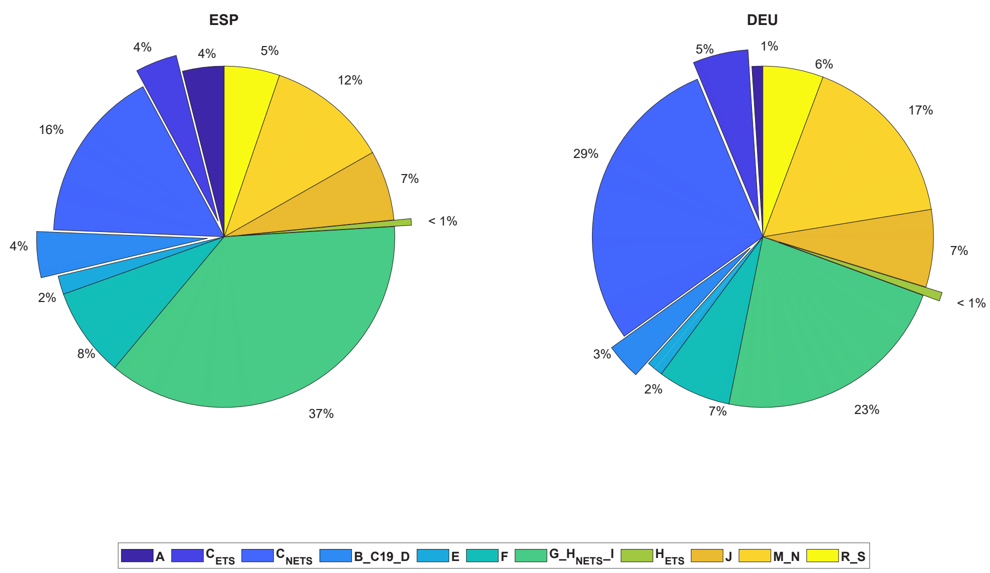
The remainder of the paper is organized as follows. Section 2 motivates the focus on Germany and Spain. The model is introduced in Section 3, its calibration in Section 4. Section 5 presents simulation setup and results and Section 7 concludes.

2. Why Germany and Spain?

The aim of this paper is to provide insights on the regional effects of carbon pricing within Europe. As the European union (EU) consists of 27 member states, a natural question to ask is why the focus is on Germany and Spain. Analysing the effects of carbon pricing on the first and the fourth largest economies within the EU has its own merits. However, there are at least three more appealing facts motivating a comparison between these countries.

The first is related to the economies' sectoral compositions. Figure 1 compares the sectoral shares in gross output. It illustrates the German economy's strong orientation towards manufacturing. The size of the German manufacturing sector (C_ETS and C_NETS) is almost twice as large as the one in Spain. At the same time, the service sector including gastronomy and hotels (G_H_NETS_I) is larger on the Iberian Peninsula, representing obvious comparative advantages of mediterranean countries. Sectors that fall under the European emission trading system (ETS) are of similar size in both countries (see shifted pie slices).

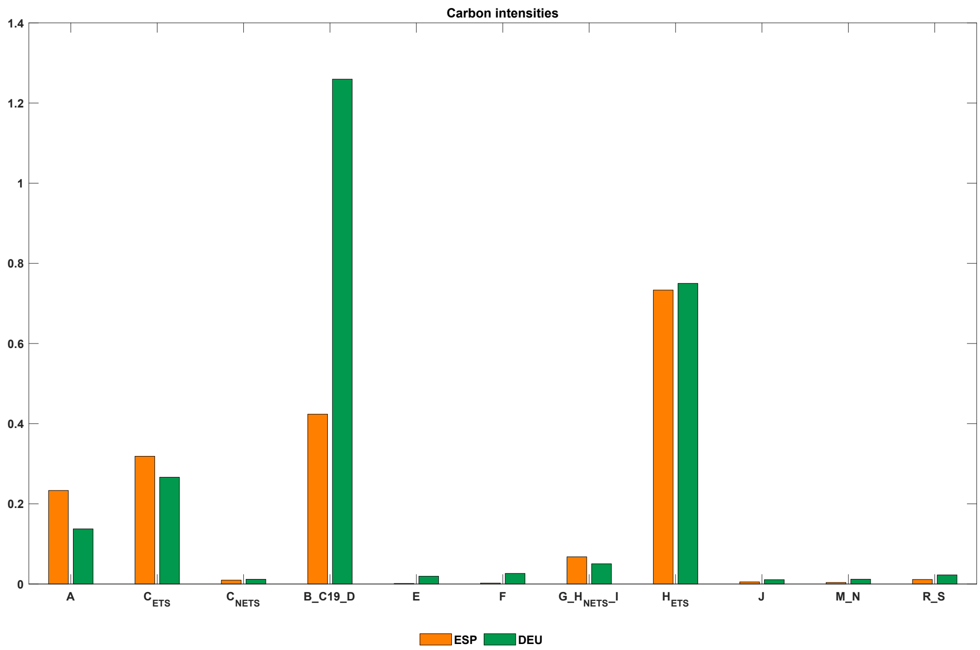
Figure 1: Comparison of sectoral shares in gross output



Notes: Figure shows sectoral shares in gross output for Spain (left) and Germany (right) taken from WIOD 2014. Sectors under ETS are offset from the pie plot.

The second reason for the regional choice are differences in emission intensities as Figure 3 reveals. While the dirtiest sector in Germany is the energy composite sector (B_C19_D), its Spanish counterpart is remarkably cleaner. In Spain, the dirtiest sector is the transport sector under ETS (H_ETS). However, overall the emission intensity is smaller in Spain than in Germany except for the agricultural, manufacturing under ETS and retail, non-ETS transport, food and accomodation service sectors. (A, C_ETS and G_H_NETS_I, respectively).

Figure 2: Comparison of carbon intensities between Germany and Spain



Notes: Figure shows sectoral carbon intensities for Spain (orange) and Germany (green) computed using data from WIOD 2014 and environmental accounts.

Third, the chosen countries differ in their trade openness measured by the sum of exports and imports of goods and services as a percentage of GDP. It amounts to 84.6 % in Germany and 63.9 % in Spain. While the import shares differ only by 8.6 PP, Germany exports 12.1 PP more.[2]

All of these structural country characteristics influence the impact and transmission mechanisms of carbon pricing and border adjustment mechanisms. Hence, comparing Germany and Spain might serve as a benchmark for other countries with similar attributes.

3. The model

Since this paper imitates the analysis of Ernst et al. (2023) using different calibrations, the model description is identical to theirs. We would also like to refer the reader to their paper for an comprehensive overview of related literature. Readers familiar with the multi-regional version of *EMuSe* might skip this section and continue with Section 4.

Our model is a multi-region extension of the multi-sector model *EMuSe* presented by Hinterlang et al. (2022). Specifically, it adds international linkages between sectoral goods and assets, world-wide emission flows as well as border adjustment taxation. Time is discrete, denoted by t and runs forever. The model consists of $\mathcal{S} = \{1, 2, .., S\}$

[2] The presented numbers refer to WIOD 2014 values. Trade openness has increased in both countries since then, but the relative sizes remain roughly the same.

production sectors and three regions $i = a, b, c$. World population is normalized to unity such that ω^i indicates (relative) population size of region i, i.e. $\omega^a + \omega^b + \omega^c = 1$.

Each region consists of a representative household, perfectly competitive labor and capital agencies, consumption, investment, and intermediate-goods retailers, as well as a fiscal authority. The former earns income from labor and capital from respective agencies that transfer them to sectoral goods producers. Labor cannot move across regions and only imperfectly across sectors. The latter also holds for physical capital. International capital mobility is captured by trade in international interest-bearing assets. Hence, for investing in foreign capital, domestic households must purchase international assets (i.e. lend money to the foreign household). The foreign household can use these funds to invest them in foreign capital, while the domestic household receives interest payments from her. Households choose how to spend their income on consumption or investment in physical capital as well as international bonds.

Competitive retailers transform sectoral output into bundles of consumption, investment, and intermediate goods. Besides the purchase of intermediate input bundles, firms use capital and labor for production, rented from the respective agencies. Production is heterogenous with respect to factor intensities and inter-sectoral linkages. Producers are price setters and prices may differ across sectors due to different markups. All goods are traded internationally.

Emissions are assumed to be a by-product of production, where the intensity may vary across sectors. Firms can engage in costly abatement and may face production damage depending on the world-wide stock of pollution. A fiscal authority runs a balanced budget by paying out lump-sum transfers and receiving income from labor income, consumption, emissions and border adjustment taxation. The model is described more formally in the following. Unless otherwise indicated, variables are expressed in (regional) per-capita terms.

3.1. Representative household

A representative household in region i chooses consumption $C_{i,t}$, labor supply $N_{i,t}$, physical capital investments $I_{i,t}$ and purchases of internationally traded assets $nfa_{i,t}$ in order to maximize expected utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left(C_{i,t} - \kappa_{i,N} \cdot N_{i,t}^{\psi} \cdot O_{i,t}\right)^{1-\sigma} - 1}{1-\sigma} \right]. \tag{1}$$

We follow the GHH preference specification as given by Jaimovich and Rebelo, 2009), which shut off the wealth effect on the labor supply (see Greenwood et al., 1988). The parameter σ denotes the inverse of the elasticity of intertemporal substitution. As $\sigma \to 1$, utility is log. β is the discount rate. The curvature of labor supply disutility is determined by ψ, and $\kappa_{i,N}$ is its weight relative to consumption. Note that we allow only the latter parameter to be region-specific. $O_{i,t} = O_{i,t-1}^{1-\gamma^{ghh}} \cdot C_{i,t}^{\gamma^{ghh}}$ makes preferences non-time-separable in consumption and labor. $\mathbb{E}_0$ is the expectations operator at $t = 0$. Given the consumer price index (CPI) in region i, $P_{i,t}^C$, the choices of the representative household are subject to the real budget constraint

$$\begin{aligned}(1+\tau_{i,t}^c)C_{i,t} + (1+\tau_{i,t}^I)P_{i,t}^I\left(I_{i,t} + S(I_{i,t}, K_{i,t-1})\right) \quad + \quad nfa_{i,t} &= w_{i,t}N_{i,t} + r_{i,t}^k K_{i,t-1} \\ &+ R_{i,t-1}nfa_{i,t-1} + TR_{i,t} + \Pi_{i,t}, \end{aligned} \tag{2}$$

where $P^I_{i,t}$ is the regional CPI-deflated real price of a basket of investment-goods, $I_{i,t}$ the corresponding basket of investment-goods, $w_{i,t}$ the real wage rate and $r^k_{i,t}$ the real rental rate of capital $K_{i,t}$. $R_{i,t}$ is the gross regional CPI-deflated real interest rate on regional holdings on net foreign assets. The average tax rate on the consumption bundle is $\tau^c_{i,t}$ and on the investment bundle $\tau^I_{i,t}$. $TR_{i,t}$ are lump-sum transfers received from the government and $\Pi_{i,t}$ denote aggregate firm profits. Capital accumulation is represented by the following law of motion

$$K_{i,t} = (1-\delta_i)K_{i,t-1} + I_{i,t}, \tag{3}$$

with δ_i denoting the regional rate of depreciation. $S(I_{i,t}, K_{i,t-1}) = \kappa^I_i/2 \cdot (I_{i,t}/K_{i,t-1} - \delta_i)^2$ are capital adjustment costs as in Ireland (2003) and Hinterlang et al. (2023b). First-order conditions are standard (see Appendix A of Ernst et al. (2023)).

3.2. Consumption and investment-goods retailers

Consumption and investment goods ($C_{i,t}$ and $I_{i,t}$) traded at prices $P^C_{i,t}$ and $P^I_{i,t}$, respectively. These goods are bundled by a perfectly competitive, representative retailer, containing sector-level consumption and investment goods of the S sectors, $C_{s,i,t}$ and $I_{s,i,t}$:

$$X_{i,t} = \left[\sum_{s=1}^{S} \psi_{X,s,i}^{1-\sigma_{X,i}} X_{s,i,t}^{\sigma_{X,i}}\right]^{\frac{1}{\sigma_{X,i}}},$$

where $X \in \{C, I\}$. The parameters $\psi_{X,s,i}$ and $\sigma_{X,i}$ determine the weight in the consumption/investment bundle and the elasticity of substitution between sector-level consumption/investment goods in region i, respectively. The representative retailer's optimization problem in CPI-deflated real terms can be written as

$$\max_{X_{s,i,t}} (1+\tau^X_{i,t}) P^X_{i,t} X_{i,t} - \sum_{s=1}^{S} (1+\tilde{\tau}^X_{s,i,t}) P^X_{s,i,t} X_{s,i,t},$$

where $P^X_{s,i,t}$ is the CPI-deflated price of sectoral consumption/investment good $s \in \mathcal{S}$. It depends on the amounts of goods purchases domestically and abroad, which is given in more formal detail below. $\tilde{\tau}^X_{s,i,t}$ is the corresponding average tax rate for this good, also depending on where the good is produced and on whether or not border adjustment taxes apply.

3.3. Labor and capital agencies

As mentioned above, labor and the physical capital stock are not perfectly mobile across sectors, and not at all across regions. Hence, we assume that a perfectly competitive, representative regional labor/capital agency hires the total amount of labor/capital, $N_{i,t}$ and $K_{i,t}$, at the CPI-deflated real wage/capital interest rate, $w_{i,t}$ and r^K_t, and sells it to intermediate goods producers operating in S different domestic sectors, such that

$$X_{i,t} = \left[\sum_{s=1}^{S} \omega_{X,i,s}^{1-\nu_{X,i}} X_{s,i,t}^{\nu_{X,i}}\right]^{\frac{1}{\nu_{X,i}}},$$

where $X \in \{N, K\}$. $\omega_{X,i,s}$ represents the sectoral weights in the labor and capital supply, $s \in \mathcal{S}$, and $\nu_{X,i}$ determines the elasticity of substitution of labor/capital across sectors. This captures the degree of (imperfect) labor/capital mobility. The labor/capital agency's optimization problem can be written as

$$\max_{X_{s,i,t}} \tilde{p}_{s,i,t} X_{s,i,t} - \tilde{p}_{i,t} \cdot X_{i,t},$$

where $\tilde{p} \in \{w, r^k\}$.

3.4. Production

In each sector $s \in \mathcal{S}$ in region $i \in \{a,b,c\}$, a monopolistically competitive firm $z \in [0,1]$ produces a differentiated sectoral variety $y_{s,i,t}(z)$ by transforming labor, $N_{s,i,t}(z)$, capital, $K_{s,i,t-1}(z)$, and a bundle of intermediate inputs, $H_{s,i,t}(z)$. The differentiated sectoral variety is sold at price $P_{s,i,t}(z)$ to a representative wholesaler who aggregates varieties into a single sectoral good $Y_{s,i,t}$ and sells these wholesale goods to households and investors according to the consumption and investment demand baskets previously described at a price $P_{s,i,t}$. Operating under perfect competition, the optimization problem of the representative wholesaler is given by

$$\max_{y_{s,i,t}(z)} P_{s,i,t} Y_{s,i,t} - \int_0^1 P_{s,i,t}(z) y_{s,i,t}(z)\, dz \quad \forall s \in \mathcal{S} \quad and \quad i \in \{a,b,c\}$$

subject to

$$Y_{s,i,t} \leq \left(\int_0^1 y_{s,i,t}(z)^{\frac{\theta^P_{s,i}-1}{\theta^P_{s,i}}}\, dz \right)^{\frac{\theta^P_{s,i}}{\theta^P_{s,i}-1}}.$$

The parameter $\theta^P_{s,i} > 1$ governs the elasticity of substitution between different varieties and may differ across sectors. This yields standard variety demand functions and sectoral prices.

The production technology of a monopolistically competitive firm z in sector s and region i exhibits constant returns to scale and is given by

$$y_{s,i,t}(z) \leq \left[1 - D_{s,i}\left(M_t\right)\right] \varepsilon_{s,i,t} \left(K_{s,i,t-1}(z)^{1-\alpha_{N,s,i}} N_{s,i,t}(z)^{\alpha_{N,s,i}} \right)^{\alpha_{H,s,i}} \left(H_{s,i,t}(z)\right)^{1-\alpha_{H,s,i}}. \quad (4)$$

Total factor productivity is denoted by $\varepsilon_{s,i,t}$, the α's determine factor intensities and $D_{s,i}\left(M_t\right)$ is a region-specific damage function that positively depends on the world emission stock M_t. As in Heutel (2012), we assume that emissions-induced damage is given by $D_{s,i}\left(M_t\right) = \gamma_{0,i} + \gamma_{1,i} \cdot M_t + \gamma_{2,i} \cdot M_t^2$. Furthermore, damage is assumed to only affect production. However, climate change may also affect welfare directly via utility damages, as shown in Barrage (2020). As checked by Ernst et al. (2023), the latter does not change the results qualitatively.

Following Annicchiarico and Di Dio (2015), emissions are a by-product of production taking the form $Z_{s,i,t} = \kappa_{s,i} \cdot (1 - U_{s,i,t}) \cdot y_{s,i,t}$, where $\kappa_{s,i} \in [0, \infty)$ denotes the emissions intensity before abatement $U_{s,i,t} \in [0,1)$. The latter is costly according to an abatement cost function $C\left(U_{s,i,t}\right) = \phi_{1,i} \cdot U_{i,t}^{\phi_{2,i}} \cdot y_{s,i,t}$, where $\phi_{1,i} > 0$ and $\phi_{2,i} > 1$ (see Annicchiarico and Di Dio, 2015, Annicchiarico et al., 2018, and Annicchiarico and Diluiso, 2019, for a discussion). Taking factor prices and acknowledging the symmetric equilibrium (which allows dropping the index z), we get the standard first-order conditions for labor, capital, intermediate inputs and abatement.

Analogously to consumption/investment goods bundles, we determine factor demand for sector j-intermediates by sector s in each region i, with $j, s \in \mathcal{S}$. Specifically, intermediates are bundled according to

$$H_{s,i,t} = \left[\sum_{j=1}^{S} \psi_{H,s,j,i}^{1-\sigma_{H,s,i}} H_{s,j,i,t}^{\sigma_{H,s,i}} \right]^{\frac{1}{\sigma_{H,s,i}}} \quad \forall s, j \in \mathcal{S} \quad and \quad i \in \{a, b, c\}.$$

Hence, the CES aggregator for each sector $s \in \mathcal{S}$ aggregates the intermediate goods from all sectors $j \in \mathcal{S}$, after weighting them by the parameter $\psi_{H,s,j,i}$ and taking into account the elasticity of substitution between those intermediate goods which is determined by $\sigma_{H,s,i}$. These parameters may differ across sectors. The optimization problem is

$$\max_{H_{s,j,i,t}} (1 + \tau_{s,i,t}^{H}) P_{s,i,t}^{H} H_{s,i,t} - \sum_{j=1}^{S} (1 + \tilde{\tau}_{j,i,t}^{H}) P_{j,i,t} H_{s,j,i,t} \quad \forall s, j \in \mathcal{S} \quad and \quad i \in \{a, b, c\},$$

where $\tilde{\tau}_{s,i,t}^{H}$ is the average tax rate on intermediate input s (again depending on whether purchased at home or abroad when differentiated taxation applies, which we will discuss below). The demand functions are standard.

3.5. Policy

Transfers are set such that the fiscal authority in region i runs a balanced budget each period:

$$TR_{i,t} = \tau_{i,t}^{c} \cdot C_{i,t} + \tau_{i,t}^{I} \cdot P_{i,t}^{I} \cdot I_{i,t} + \sum_{s=1}^{S} P_{s,i,t}^{em} \cdot Z_{s,i,t} + \sum_{s=1}^{S} \tau_{s,i,t}^{H} \cdot P_{s,i,t}^{H} \cdot H_{s,i,t}. \tag{5}$$

All tax rates are given exogenously or derived according to the simulation design described below. Allowing for public debt and different fiscal rules along the lines of, for example, Mitchell et al. (2000), is possible in general. For a discussion about the impact of using different fiscal instrument in our model, see also Hinterlang et al. (2022).

3.6. International linkages, market clearing and aggregation

Allowing for International trade in goods and assets not only affects the net foreign asset position but also the market clearing conditions. Households and firms in region i are allowed to purchase domestic as well as foreign goods. Hence, the corresponding CES bundles for consumption, investment and intermediate goods are determined by

$$X_{s,i,t} = \left[\sum_{\tilde{i} \in \{a,b,c\}} hb_{X,s,i,\tilde{i}}^{1-\sigma_{X,s,i,\tilde{i}}} X_{s,i,\tilde{i},t}^{\sigma_{X,s,i,\tilde{i}}} \right]^{\frac{1}{\sigma_{X,s,i,\tilde{i}}}} \quad \forall s \in \mathcal{S} \quad and \quad i, \tilde{i} \in \{a, b, c\},$$

where $X \in \{C, I, H\}$.[3] The parameter $hb_{X,s,i,\tilde{i}}$ is the sector-s preference bias of region i towards goods produced in region $\tilde{i}$. Hence, $hb_{X,s,i,i}$ can be interpreted as home bias. $\sigma_{X,s,i,\tilde{i}}$ is the corresponding elasticity of substitution between home and foreign goods. Given bundle, (potentially) sector and region-specific taxes for each good, the optimization problem in CPI-deflated real terms can be written as

[3]Note that the bundles should actually be denoted by $C_{s,i,t}$, $I_{s,i,t}$ and $H_{s,j,i,t}$, and the corresponding inputs by $C_{s,i,\tilde{i},t}$, $I_{s,i,\tilde{i},t}$ and $H_{s,j,i,\tilde{i},t}$. We subsume these indices in the X's to save space.

$$\max_{X_{s,i,\tilde{i},t}}(1+\tilde{\tau}^{X}_{s,i,t})P^{X}_{s,i,t}X_{s,i,t}-\sum_{\tilde{i}\in\{a,b,c\}}^{S}(P_{s,i,\tilde{i},t}+\tau^{X}_{s,i,\tilde{i},t})X_{s,i,\tilde{i},t}\quad \forall s\in\mathcal{S}\quad and\quad i\in\{a,b,c\},$$

where $P_{s,i,\tilde{i},t}$ is the producer price of region $\tilde{i}$ deflated by CPI of region i (see derivation below). $\tau^{X}_{s,i,\tilde{i},t}$ denotes region i's quantity tax on goods of sector s that are produced in region $\tilde{i}$ and purchased in region i. It is a policy variable, and we allow policy makers to differentiate between taxes in the consumption, investment and intermediate goods bundles. If region i wants to discriminate imports by a border adjustment tax, it must hold that $\tau^{X}_{s,i,\tilde{i},t} > \tau^{X}_{s,i,i,t}$ for $i \neq \tilde{i}$. These tax rates are exogenously given as specified in detail when describing the simulation design below.

Given these demands for home and foreign goods, the sectoral trade balances for each region are given by

$$TB_{s,i,t}=\frac{P_{s,i,i,t}}{\omega^{i}}\cdot\sum_{\tilde{i}\neq i}\omega^{\tilde{i}}\left(C_{s,\tilde{i},i,t}+I_{s,\tilde{i},i,t}+\sum_{j=1}^{S}H_{s,j,\tilde{i},i,t}\right)-\sum_{\tilde{i}\neq i}P_{s,i,\tilde{i},t}\cdot\left(C_{s,i,\tilde{i},t}+I_{s,i,\tilde{i},t}+\sum_{j=1}^{S}H_{s,j,i,\tilde{i},t}\right)\quad (6)$$

for all sectors s and regions i. Note that, for exports, we have to take into account country size as the other variables are represented in regional per-capita terms. The aggregate trade balance of region i is, then, given by $TB_{i,t}=\sum_{s=1}^{S}TB_{s,i,t}$. Net foreign assets evolve according to

$$nfa_{i,t}=R_{i,t-1}\cdot nfa_{i,t-1}+TB_{i,t}\quad (7)$$

where $R_{i,t}$ is assumed to include a risk premium as in Schmitt-Grohe and Uribe (2003), among others.[4]

We can also measure how emissions embodied in international trade in our model move across regions. The sector-specific emissions content of net imports of region i is given by

$$\begin{aligned}EC_{s,i,t} \;=\; & \sum_{\tilde{i}\neq i}\kappa_{s,\tilde{i}}\cdot(1-U_{s,\tilde{i},t})\cdot\left(C_{s,i,\tilde{i},t}+I_{s,i,\tilde{i},t}+\sum_{j=1}^{S}H_{s,j,i,\tilde{i},t}\right)\\ & -\sum_{\tilde{i}\neq i}\frac{\omega^{\tilde{i}}}{\omega^{i}}\cdot\kappa_{s,i}\cdot(1-U_{s,i,t})\cdot\left(C_{s,\tilde{i},i,t}+I_{s,\tilde{i},i,t}+\sum_{j=1}^{S}H_{s,j,\tilde{i},i,t}\right),\end{aligned}\quad (8)$$

and measures sector-specific emissions that are imported (or exported, if negative). Dividing $EC_{s,i,t}$ by $Z_{s,i,t}$ gives a measure of the sector-specific "net carbon leakage" share following the idea of Su et al. (2010), Chen and Chen (2011) and Sato (2014), among others. If $EC_{s,i,t}/Z_{s,i,t}$ increases after a policy change, more emissions-intensive goods are imported relative to domestic production of these goods and we have (relative) carbon leakage. The opposite is true if this value falls. Summing over all sector s then measures this share for region i.

It remains to derive some inter-regional prices. When region i buys a product of region $\tilde{i}$ from sector s, region $\tilde{i}$ sells it at its own CPI-deflated producer price $P_{s,\tilde{i},t}$. For

[4] In standard open-economy DSGE models along the lines of Obstfeld and Rogoff (1995), which we also have here, the net foreign asset position is exogenous (zero in our initial steady state). Stationarity is reached by adding a friction to the financial market that kicks in whenever the exogenously fixed reference level is missed (see Schmitt-Grohe and Uribe, 2003, Hunt and Rebucci, 2005, Lubik, 2007 and Benigno, 2009, for a discussion). The risk premium does the job in our model.

country i, this has to be translated by using its own CPI deflator. Hence, $P_{s,i,\tilde{i},t} = P_{s,\tilde{i},t} \cdot P^C_{\tilde{i},t}/P^C_{i,t}$, where the latter ratio of consumer prices yields the real exchange rate between the two region: $rer_{i,\tilde{i},t} = P^C_{\tilde{i},t}/P^C_{i,t}$. As internationally traded assets are in zero net supply, we can use this to show that $\omega^c \cdot nfa_{c,t} = -rer_{a,c,t} \cdot \omega^a \cdot nfa_{a,t} - rer_{a,b,t} \cdot \omega^b \cdot nfa_{b,t}$ must hold.

In each sector s and region i, product market clearing implies

$$P_{s,t}y_{s,t} = P^C_{s,t}C_{s,t} + P^I_{s,t}I_{s,t} + TB_{s,i,t} + \sum_{\tilde{s}=1}^{S} P_{s,h,t}H_{\tilde{s},s,t} + \phi_{1,s,i} \cdot U^{\phi_{2,s,i}}_{s,i,t} \cdot y_{s,t}.$$

We define an emission cost factor $ec_{s,i,t}$ as the sum of abatement costs and emission taxes, i.e. $ec_{s,i,t} = \left[\phi_{1,s,i} \cdot U^{\phi_{2,s,i}}_{s,i,t} + P^{em}_{s,i,t} \cdot \kappa_{s,i} \cdot (1 - U_{s,i,t})\right]$. Only the former appears in the sectoral resource constraint (as the latter is redistributed back to households through policy). Defining aggregate output as gross value added, we get

$$Y^{va}_{i,t} = C_{i,t} + P^I_{i,t} \cdot I_{i,t} + TB_{i,t} + P^I_{i,t}S(I_{i,t}, K_{i,t-1}). \tag{9}$$

Given that we expressed most variables in (regional) per-capita terms above, total regional emissions are given by $Z_{i,t} = \sum_{s=1}^{S} \omega^i \cdot Z_{s,i,t}$, world emissions by $Z_t = \sum_{i\in\{a,b,c\}} Z_{i,t}$, and the world emission stock, which is responsible for damage, evolves according to

$$M_t = (1 - \rho^M) \cdot M_{t-1} + Z_t. \tag{10}$$

$\rho^M \in (0, 1)$ determines how fast additional emissions are relieved.

This completes the model description. All decisions must be such that they are mutually consistent and the above equations hold.

4. Calibration

The *EMuSe* model always comprises three parameter sets. The first concerns general parameters. Regarding these, we rely on the values of Ernst et al. (2023), except for regional sizes, which we adjust to our country choices. The second set consists of the sector-specific parameters, which can be calibrated for a custom choice of regions and sectors using the *EMuSe* Calibration Toolkit (see Hinterlang et al. (2023a)). It includes capital and labor shares, factor intensities, input-output linkages and contributions to final demand. Finally, the third set of parameters correspond to the environmental module of the model. It captures carbon intensities (also provided by the Calibration Toolkit) and parameters of the abatement costs and damage function.

For the analysis at hand, we calibrate the model twice each with three regions (a,b,c) but grouping countries differently. First, we calibrate it to Germany, the remaining EU27 countries (plus UK, Norway and Switzerland) and the rest of the world. Second, we calibrate region a to Spain instead of Germany with the same counterparts as described before. The formation of region b is explained by the fact that these countries either directly participate in the European Union Emissions Trading System (EU-ETS) or have established a compatible system. In the following, we will refer to this region as rest of Europe. To save space, we relegate all detailed calibration tables to Appendix A.

General parameters. The model is calibrated to the quarterly frequency. Population data, needed to compute relative sizes and relative value added per capita of the regions, is taken from the United Nation's World Population Prospects for 2020. We choose a discount factor of $\beta = 0.985$. Following Jaimovich and Rebelo, 2009, we set $\sigma = 1$ and

$\gamma^{ghh} = 0.001$. Along the lines of Coenen et al. (2013), we calibrate the Frisch elasticity of labor supply to 0.5 (i.e. $\Psi = 2$). The relative weights of region-specific disutility of labor $\kappa_{i,N}$, $i = a, b, c$ target an aggregate labor supply of $\bar{N}_i = 0.33$. Capital depreciates at a typical annual rate of 10% (see, for example, Cooley and Prescott (1995)) and the respective adjustment cost parameter κ^I is fixed at 25. The consumption tax rate amounts to 0.2 in all regions. Substitution elasticities for goods produced in the different sectors are determined as follows. Along the lines of Atalay (2017) and Baqaee and Farhi (2019) we choose a value of 0.9 for the consumption basket. Regarding the investment goods basket, we assume a lower elasticity of substitution of 0.75. Following Bouakez et al. (2023) and Atalay (2017), we select the value for intermediate inputs at 0.3. Baqaee and Farhi (2019) allow for a higher substitution elasticity (of 0.4). However, changing the value does not alter our results qualitatively and only mildly quantitatively (the adjustment of relative prices is mitigated). This is also true for the elasticity between home and foreign goods, which we set close to one. Labor and capital can be substituted quite easily in our model with a substitution elasticity of 10. We do not have to assume perfect substitutability as in Bouakez et al. (2023), but the system can no longer be solved for too low values. See Antoszewski (2019) for a critical discussion. To facilitate calculations, we also normalize relative prices to one in the initial steady state.

Sector-specific production parameters. Relying on the standard NACE Rev. 2 classification, we distinguish between $S = 11$ producing sectors in three regions ($i \in \{a, b, c\}$). We have two manufacturing (MF) sectors, where we group sectors according to the applicability of the ETS. Hence, manufacturing (ETS) includes MF of (i) paper and paper products (C17), (ii) chemicals and chemical products (C20), (iii) other non-metallic mineral products (C23) and (iv) basic metals (C24).[5] We further build a *energy* sector composite of mining, quarrying (B), MF of coke and refined petroleum (C19) and energy (D) and separate the transport sectors that fall under ETS, which are water (H50) and air (H51) transport.[6] See Table 1 for an overview of the modeled regions and sectors.

Table 1: Choice of regions and sectors

Regions:	
a :	DEU or ESP
b :	Rest of EU27, CHE, NOR, UK
c :	AUS, BRA, CAN, CHN, IDN, IND, JAP, KOR, MEX, RUS, TUR, TWN, USA, ROW
Sectors:	
1)	Agriculture, forestry and fishing (A)
2)	Manufacturing (C_ETS)
3)	Manufacturing (C_Non-ETS)
4)	Mining, quarrying, manufacturing of coke and refined petroleum & energy (B_C19_D)
5)	Water supply (E)
6)	Construction (F)
7)	Wholesale & retail trade, transp. and storage (Non-ETS), accomod. & food (G_H_NETS_I)
8)	Transport (H_ETS)
9)	IT and communication
10)	Prof., scient. and techn. & admin. and support services (M_N)
11)	Arts, entertainment, recreation & oth. services (R_S)

Notes: The table gives an overview of the modeled regions and sectors.

[5]In most cases, only subsectors of these sectors fall under ETS. However, we lack more disaggregated data for calibration. Moreover, note that we exclude the sections activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (T) and activities of extraterritorial organizations and bodies (U).

[6]Note that the water transport sector is actually not yet included in the ETS. Since there are plans to do so, we subsume it under the transport under ETS sector.

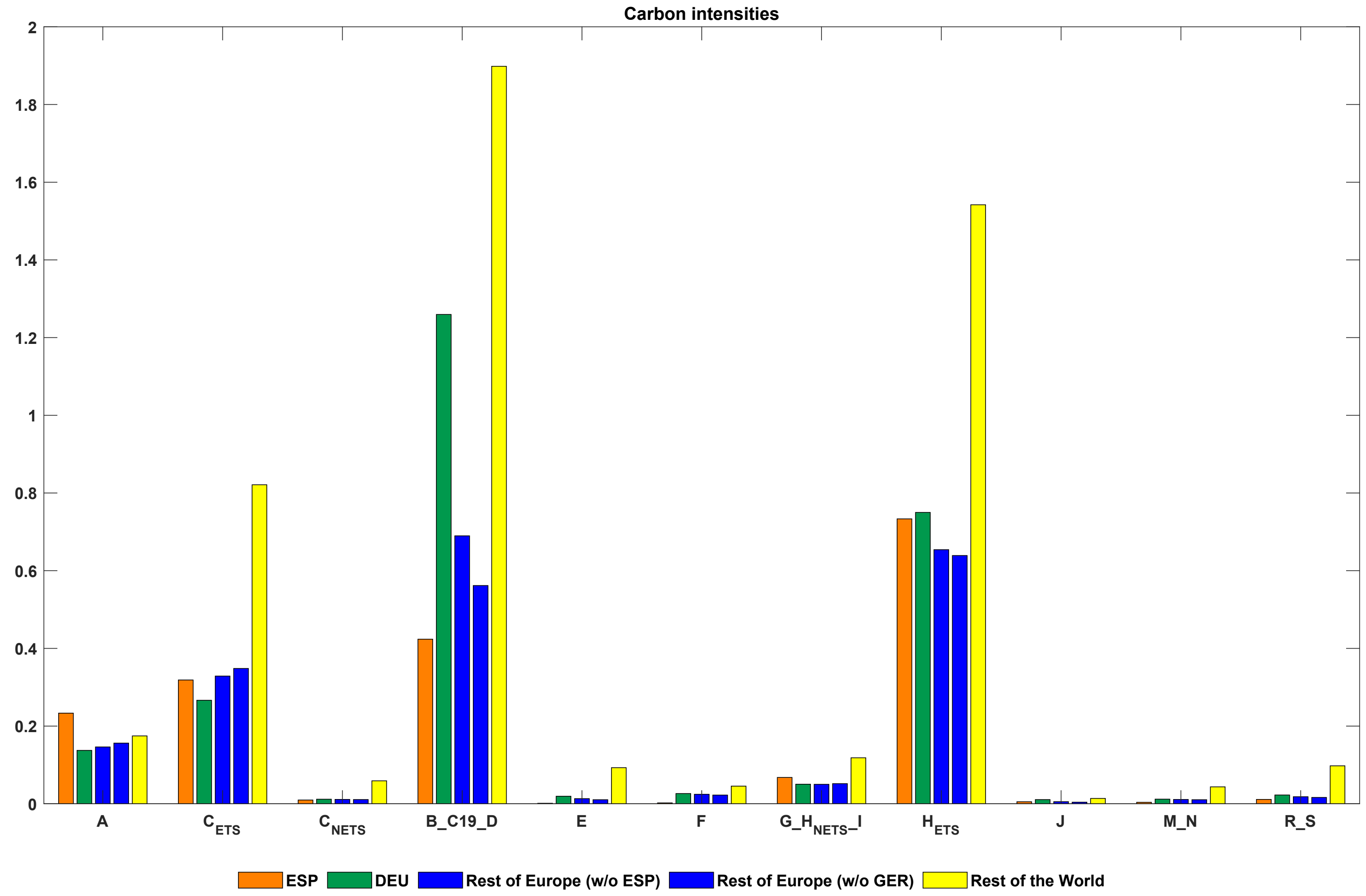
The sectors differ along several dimensions. In the model, sectoral shares in labor and capital bundles are given by $\omega_{N,s,i}$ and $\omega_{K,s,i}$, respectively. Moreover, we allow for heterogenous production technologies of intermediate goods producers by different factor intensities for labor, capital and intermediate inputs. Furthermore, all sectors contribute differently to final demand. All of these sector-specific parameters are derived using the most recent release of the World Input-Output Database (WIOD), covering the years 2000-2014 (see Timmer et al., 2015) and we rely on 2014 values. It includes data on socioeconomic accounts as well as input-output tables for 56 sectors and 43 countries. We build three country aggregates as outlined above. Using the socioeconomic accounts (SEA), we determine the sector-specific labor and capital supply $\omega_{N,s,i}$, $\omega_{K,s,i}$, as well as factor intensities $\alpha_{N,s,i}$ and $\alpha_{H,s,i}$ in each region.[7] In order to determine the former, we compute the sector-specific shares in the cumulated number of persons engaged and the nominal capital stock over all sectors. The factor intensities for intermediate inputs, $1 - \alpha_{H,s,i}$ are computed by dividing the amount of intermediate inputs by gross output per industry. The values for $\alpha_{N,s,i}$ can then be fixed using the share of labor compensation in gross output. Parameters $\psi_{H,s,j,i}$ describe the share of intermediate inputs consumed by sector s that are produced by sector j. These are calibrated using the input-output tables by first computing the total sum of intermediate inputs for each sector and then the respective shares of the producing sector. Following the same routine, we can compute the preference bias parameters $hb_{H,s,i,\bar{i}}$ of region i towards intermediate goods produced in region $\bar{i}$. The distribution of final consumption expenditure by households and gross fixed capital formation across sectors as mirrored by the CES bundle shares $\psi_{C,s,i}$ and $\psi_{I,s,i}$ can be derived with WIOD's national accounts data. The same holds true for the preference biases $hb_{X,s,i,\bar{i}}$, $X \in \{C, I\}$ of region i towards consumption or investment goods produced in region $\bar{i}$. Note, however, that preference biases of region c are used to close the model and might therefore deviate from the data.

Environmental parameters . To calibrate sector-specific CO2 emissions per unit of output, we use environmental accounts provided by the European Commission that are consistent with WIOD (see Corsatea et al., 2019). Information on sectoral emissions is available from 2000-2016. However, we are restricted to take values from 2014, since the WIOD series end in this period and carbon intensities are computed by dividing emissions by gross output taken from there. Since we can only observe emissions after abatement efforts, we ensure that $(1 - \bar{U}_{s,i})\kappa_{s,i}$ coincides with the values in the data. As figure 3 shows, region c has the most carbon intensive production across sectors (agriculture being the only exception with the highest intensity in Spain). In Germany and the rest of the world, the energy composite sector has the largest carbon intensity and the emission intensity of this Spanish sector is remarkably low compared to the other regions. In Spain, the dirtiest sector is the transport sector under ETS. However, overall the emission intensity is smaller in Spain than in Germany (except for sectors A, C_ETS and G_H_NETS_I). Unsurprisingly, the sectors that fall under ETS (B_C19_D, C_ETS and H_ETS) are the high polluting ones across all regions.

We assume a linear decay rate for the stock of pollution of $1 - \rho^{EM} = 0.9979$ following Heutel (2012) and Annicchiarico and Di Dio (2015). The parameters of the abatement cost function are equal across sectors. While $\phi_2 = 0.185$ in all regions, ϕ_1 is region-specific and corresponds to estimates of Nordhaus, William (2007). However, due to the lack of data, we cannot distinguish the parameter between region a and b

[7] Note that SEA data is given in national currencies. We use WIODs exchange rate series to transform the data to USD.

Figure 3: Comparison of carbon intensities across regions



Notes: Figure shows sectoral carbon intensities for Spain (orange), Germany (green), the rest of Europe without the respective individual country (blue) and the rest of the world (yellow).

and have to rely on the estimate for whole Europe. A critical discussion about different abatement cost functions and their parameterizations can be found in Cline (2011). Our parametrization for the damage function implies that sectoral output losses almost double if the pollution stock increases by 10% relative to its initial steady state level. The parametrization is loosely tied to Kalkuhl and Wenz (2020) and calculations made by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS; see NGFS, 2020, 2021). We account for the fact that the economic impact of climate change differs between regions by following Nordhaus, William (2007). More specifically, we translate the emission stocks into temperature increases and use the region-specific total damage estimates at 2.5°C warming. Again, damage functions for Germany, Spain and the respective rest of Europe are assumed to be identical. Choosing a lower economic damage from emissions would reduce the damage reduction and thereby slow down the productivity increase in the simulations shown below (the opposite is true for assuming a higher damage). Simulation results when assuming no damage from emissions can be found in Appendix B.

5. Simulations

This section describes the simulated policy scenarios and their results. For the latter, we compare effects across policy scenario as well as across the two model calibrations (once with Germany and once with Spain as region a).

Policy scenarios. We consider four policy scenarios. In the first one, only the individual country a (i.e. Germany or Spain) increases carbon pricing. Second, we assume that all Europe (regions a and b) introduces the same carbon price. The third scenario represents a European climate club following the definition of Nordhaus (2015). This means that we add a border adjustment mechanism vis-a-vis the rest of the world (region c) such that the carbon content of imports from this region is taxed, while exports to region c are tax exempt. Finally, we run a global carbon pricing scenario, where all three regions introduce carbon pricing. All scenarios are conducted under perfect foresight, i.e. deterministic simulations of the fully non-linear system. The price path is credibly announced and there is no stochastic uncertainty.

The specific carbon price path $P^{em}_{s,i,t} = P^{em}_{i,t}$ is exogenously given and applies to all regions and sectors equally (depending of course on which region introduces the price).[8] Specifically, we feed the price path of the recently updated net zero emissions scenario computed by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) into the model (see NGFS, 2022, for details). It assumes that the carbon price increases quite steeply, reaching its peak in 2050 where it is almost 24 times higher than in the initial steady state, before gradually decreasing to its new steady state level, which is 13 times as large as before . Note that we assume no technological change beyond the endogenous changes in abatement in the simulation results shown below, while the REMIND model used by the NGFS includes (exogenous) technological progress. Hence, feeding the same price path in our model, does not lead to the same emissions reduction.

Regarding border adjustment, we assume that the import base tax rate equals the carbon price. Since it applies on the quantity of imported goods and carbon emissions shall be priced, we have to consider the emission intensities when computing

[8]See Appendix B for a scenario where only the ETS sectors (2,4,8) are subject to the carbon price. Results do not change qualitatively and only slightly quantitatively.

the tax rate, i.e. $\tau^X_{s,i,\tilde{i},t} = P^{em}_{i,t} \cdot \kappa_{s,\tilde{i}}$, for $\tilde{i} = c$. Moreover, exports are subsidized in the scenario with border adjustment. This means that the carbon price does not apply for the part of domestic production that is used for exports (corresponding to the full border adjustment scenario in Ernst et al., 2023). Formally, this implies that $P^{eff,em}_{s,i,t} = P^{em}_{s,i,t} \cdot \left(1 - \frac{Exp_{s,i,t}}{y_{s,i,t}}\right)$ substitutes $P^{em}_{s,i,t}$ in the model equations. All revenues from carbon pricing are distributed lump-sum to households.[9]

Results. When describing the results, we start with comparing the effects across the different policy scenarios (Figures 4 and 5). Figures 6 to 11 then highlight the differences between both model calibrations.

As can be seen in figures 4 and 5 the effect of carbon pricing can be divided into two phases. The first is characterized by a long-lasting negative impact on output in regions introducing a carbon price. The reason for this is that marginal production costs for firms increase. This translates into larger relative prices, which depress demand and income such that output, consumption and capital investment fall.

Firms increase abatement efforts due to the carbon price and their emissions fall. Hence, the world emissions stock decreases. This yields a positive productivity effect due to lower damage from emissions. When this effect is large enough, it introduces the second phase of carbon pricing, characterized by an economic upswing until a new steady state is reached. The final outcome is determined by the size of the emissions reduction, which is larger the more regions participate in carbon pricing.[10]

When only the individual country a introduces a carbon price (see red scenario), the emissions reduction is very small and so is the productivity enhancing effect. It is not large enough to overcompensate for the additional costs of the distortionary tax, such that the effect on long-run output is negative in a. Regions that do not participate in carbon pricing benefit from the emissions and damage reduction and potential trade spill-overs. At the same time, however, they also face smaller demand due to the policy induced income loss, which explains negative output effects during the transition. These are basically the results presented in Ernst et al. (2023).

As Figure 6 reveals, the Spanish economy is less affected than the German one in this first scenario. The main reason is that carbon intensities are on average smaller in Spain. Moreover, we observe that the rest of Europe and the rest of the world respond more strongly to carbon pricing in Germany than in Spain. In the beginning this is because their imports from Germany are higher than from Spain and imports become more expensive due to the carbon price. In the long run, they benefit more because the emissions reduction is larger.

Results of the second (purple) scenario actually differ from the results of Ernst et al. (2023). While in their case region a benefits immediately when region b joins carbon pricing, with the regions we model this holds only true for the long run. The reason is twofold. First, the emissions reduction is of course larger in Ernst et al. (2023) as regions a and b represent Europe and North America, respectively. Second, our region a (either Germany or Spain) has a closer trade relationship with region b (rest of Europe). Hence, the output reducing effect of carbon pricing in b also affects a more strongly. First, region b demands less products from a because people have less income. Second, imports from region b are more expensive for a. Still, both Germany and Spain are better off in the final steady state when the rest of Europe participates. This is because the emissions-

[9]See Hinterlang et al. (2022) for an analysis where revenues from emissions taxation are used to finance a labor tax reduction.

[10]Please see Appendix B for results shutting off damage from emissions. In this case, only the distortionary effects of carbon pricing prevail.

induced damage reduction is larger in this scenario. As in the first scenario, output in Spain is less affected than in Germany (see Figure 7) because emission intensities are lower.

The effects of the border adjustment mechanism in the European climate club scenario (comparing blue vs. purple) also depend on the model calibration. Generally, the border adjustment import tax has two opposing effects. On the one hand, it increases competitiveness of the introducing region as it gets less attractive to substitute domestic goods with foreign ones. This fosters output. In addition, it might reduce carbon leakage and emissions, such that output increases even further via the damage-productivity channel. On the other hand, however, it introduces another distortion to the system, reducing income in region c and making imports for the region(s) that introduce border adjustment more expensive. While the tax exemption of exports takes out some of the models' distortions, the overall effect of border adjustment depends on the specific trade relation with region c.

Indeed, it turns out that Germany as an individual country benefits from the border adjustment mechanism, while Spain loses. This aligns aggregate effects in the European climate club scenario in both countries (see Figure 8). Why does the border adjustment mechanism benefit Germany, while it hurts Spain during the transition? The reason is twofold. First, Germany exports more to the rest of the world than Spain does (compare preference biases of the rest of the world towards Germany and towards Spain given in the Appendix). Since exports are tax exempt under the border adjustment mechanism, this benefits Germany disproportionately. Second, Spain has a larger exposure towards dirty intermediate inputs from the rest of the world.[11] Hence, Spain's imports of intermediate input become relatively more expensive due to the border adjustment than the German ones. Apparently, in Spain this cost push outweighs the positive effects, yielding an overall negative effect on output during the transition. For both model calibrations, it still holds true that border adjustment reduces carbon leakage and the world emissions stock, but only to a small extent (because it mainly protects dirty domestic sectors as we will see in the following paragraph). Hence, it is no game changer and only slightly augments long-run output in Europe.

Finally, Figure 10 illustrates that Europe has a strong incentive to get the rest of the word on board. In the global carbon pricing scenario, the downturn phase is shorter in a and b and long-run benefits are larger in all regions. However, the rest of the world also faces larger transition costs in this case. These results confirm again the findings of Ernst et al. (2023) and the effects on the German and Spanish economy are pretty much aligned.

While the aggregate long-run output effects are quite similar for Germany and Spain, we can observe differences on the sectoral level. Figure 11 plots percentage deviations of sectoral value added from the new to the initial steady state and each row represents another policy scenario. In general, dirtier sectors are more affected directly by carbon pricing. In line with this, in the first scenario, the German energy composite sector (B_C19_D) faces the largest losses due to its relatively high carbon intensity. However, two sectors stand out. First, the German manufacturing sector under ETS (C_ETS) benefits in the long run, although it has a relatively large emission intensity compared to other German sectors. The reason is as follows. As shown before, long-run output of the rest of Europe and the rest of the world increase in this scenario. Since these regions (especially the rest of Europe) import a significant share of intermediate inputs of the

[11] The exposure is measured by multiplying the sectoral shares of Spain's intermediate inputs produced in region c with the respective carbon intensities of the latter and aggregating over sectors.

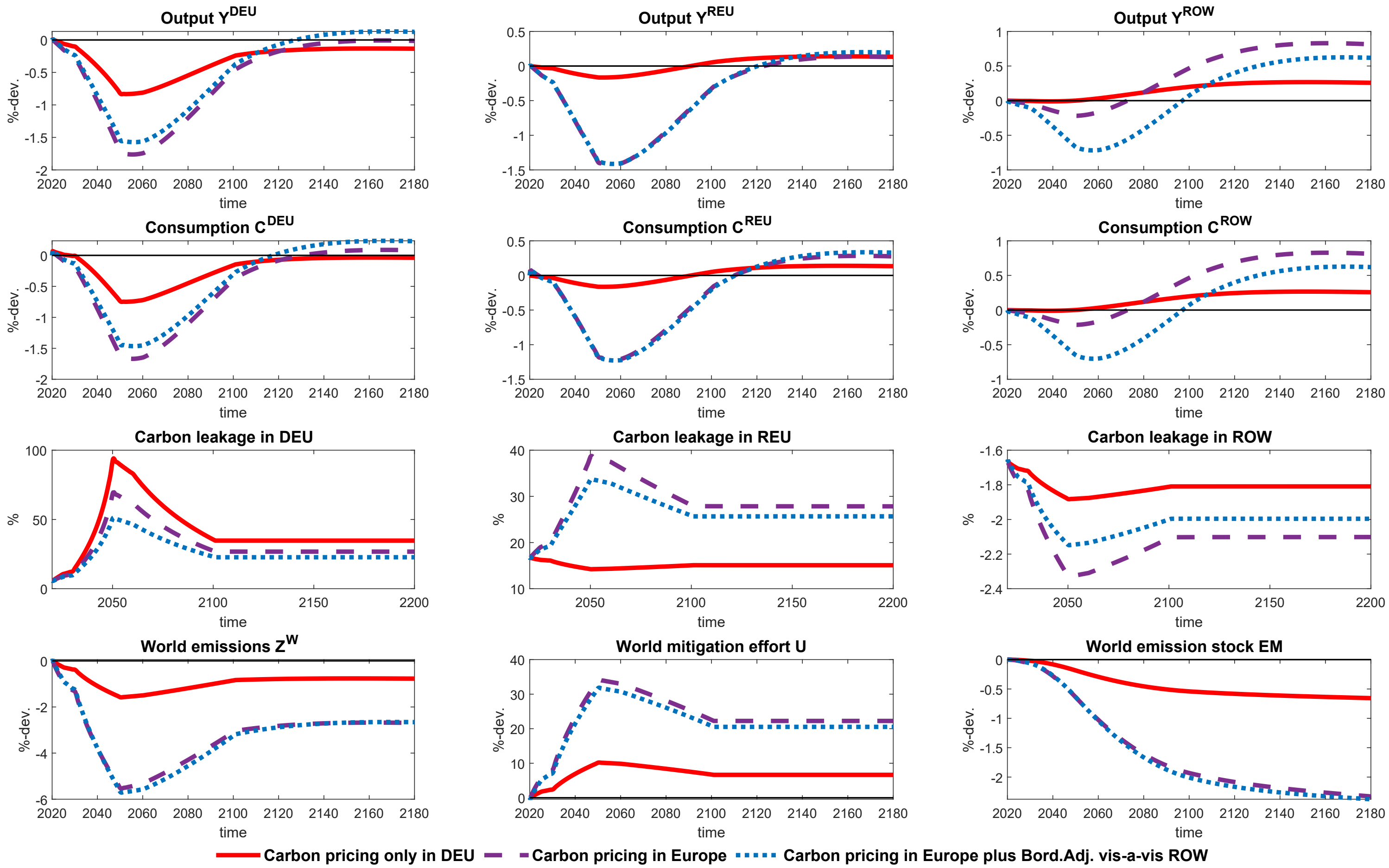
C_ETS sector from Germany, it benefits from a stronger foreign demand. Second, the result for the Spanish transport sector under ETS (H_ETS) surprises. While it is the sector with the largest carbon intensity in Spain, it loses only slightly in terms of long-run value added. This is due to two characteristics. Compared to other Spanish sectors, it exports more intermediate inputs to the rest of Europe, stabilizing long-run output (same channel as explained before). Moreover, it only weakly depends on intermediate inputs from itself. As can be seen in Table A.4, the share of intermediate inputs produced and consumed by H_ETS ($\Psi_{H,ESP,8,8}$) only amounts to 12 %. Out of these, only 16.4 % are produced domestically (see respective home bias in Table A.5). Hence, under 2 % of the intermediate inputs used by the Spanish ETS transport sector stem from its own. Therefore, it is only weakly affected by price hikes of intermediate inputs from itself.

On average, sectors are slightly better off in the long-run in the second scenario. Since whole Europe introduces carbon pricing here, the additional damage reduction effect benefits all. However, sectors that previously gained through increased demand from the rest of Europe (C_ETS in Germany and H_ETS in Spain) now lose as well. This is because the rest of Europe experiences smaller long-run income gains when it joins carbon pricing.

As in Ernst et al. (2023), sectoral results for the European climate club scenario support the view that border adjustment mainly protects dirty domestic sectors. This holds especially true for the Spanish energy composite sector (B_C19_D) which is relatively clean compared to its international counterparts, but still one of the dirtiest sectors within Spain. This explains why the additional emissions reduction by border adjustment is limited, making it no game changer. Indeed, some sectors like the C_ETS sector in Spain lose by the border adjustment mechanism. This sector suffers disproportionately from the carbon tax on imports of region c because a relatively large share of its intermediate inputs (almost 8 %) is produced by the dirtiest sectors (2,4 and 8) in the rest of the world.

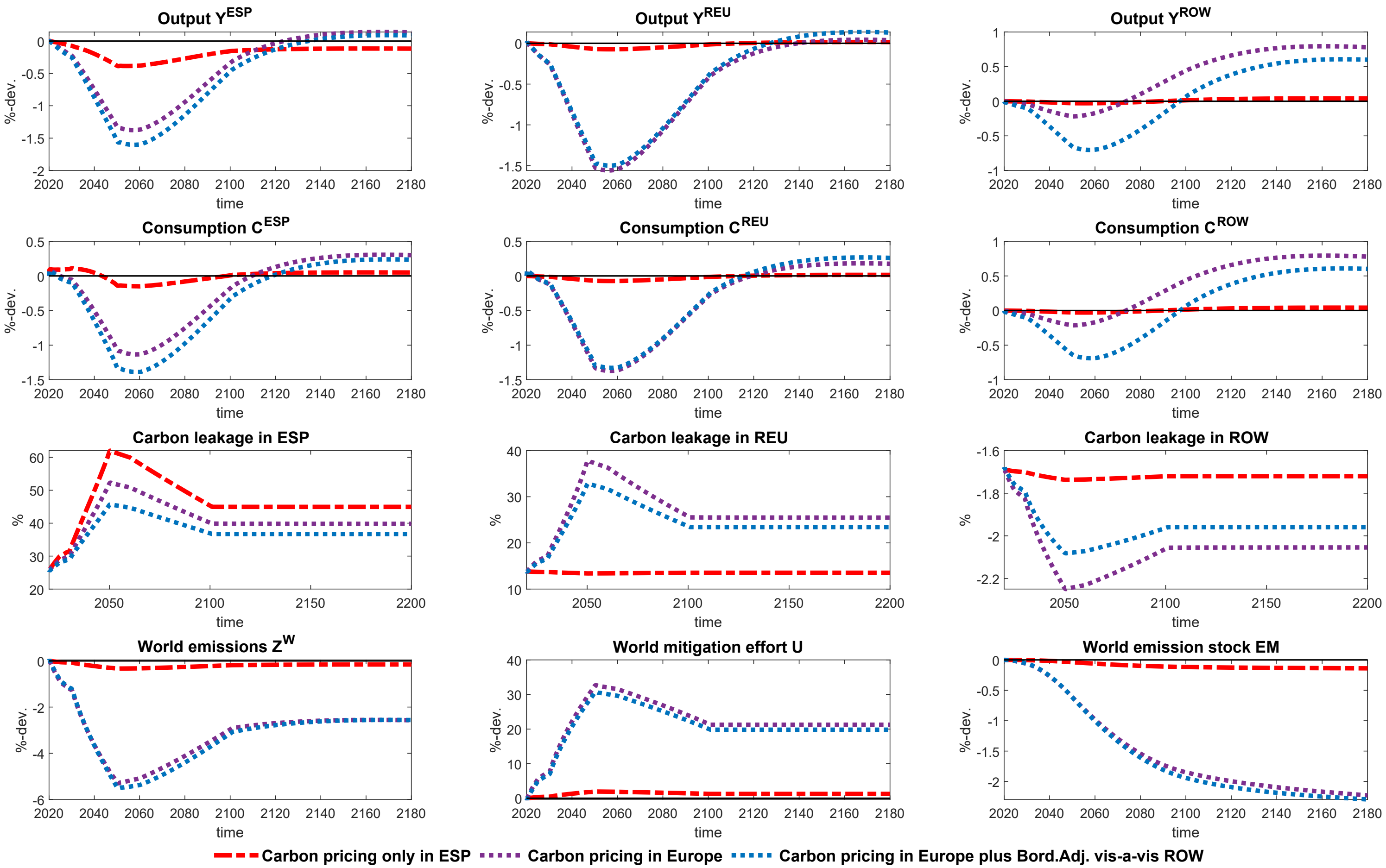
Finally, all sectors are better off in the global carbon pricing scenario. This is because of the sizeable reduction of the world emissions stock, resulting in productivity gains through less damage. The large difference between the German and Spanish energy aggregate sectors is due to the much higher carbon intensity of the German one.

Figure 4: Effects of carbon pricing on selected variables in Germany, rest of Europe and the rest of the world



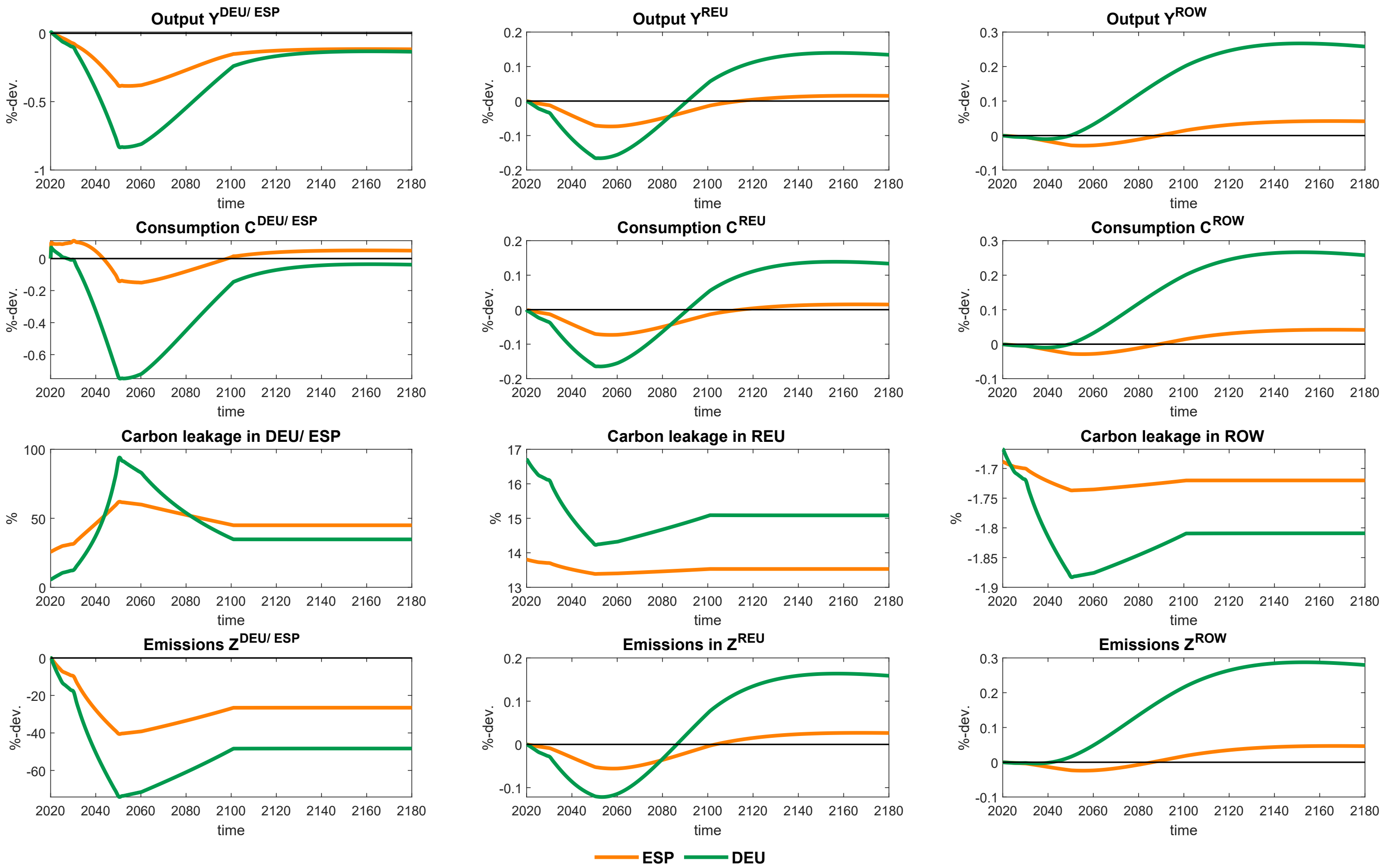
Notes: Figure plots (projected) implications of carbon pricing for selected variables in the three regions. The red dotted-dashed lines show the variables for carbon prices in region Germany (*a*) only. Carbon pricing in whole Europe (*a* and *b*) is depicted by the purple dotted line, and a European climate club including border adjustment by the dashed blue line.

Figure 5: Effects of carbon pricing on selected key variables in Spain, rest of Europe and the rest of the world



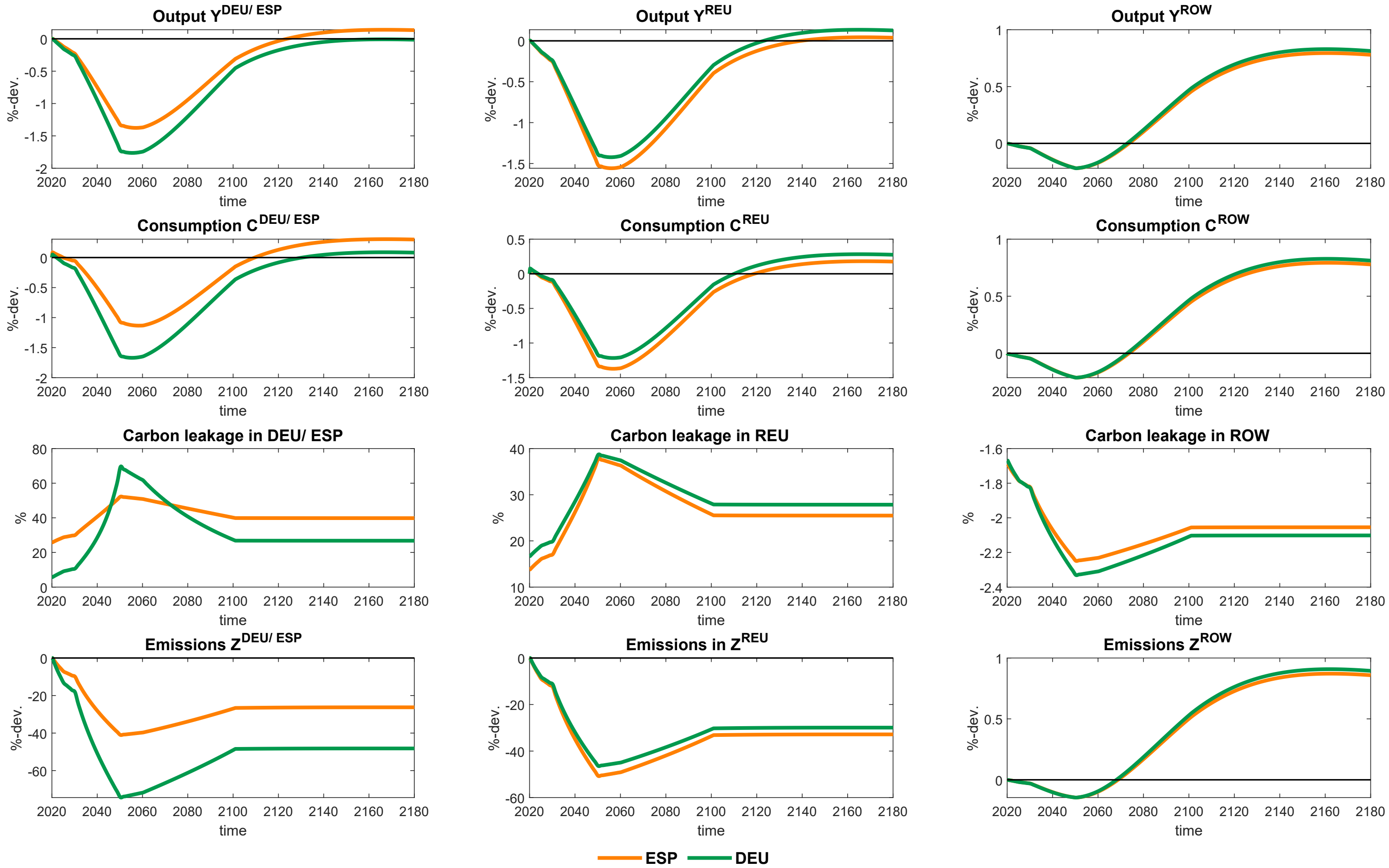
Notes: Figure plots (projected) implications of carbon pricing for selected variables in the three regions. The red dotted-dashed lines show the variables for carbon prices in region Spain (*a*) only. Carbon pricing in whole Europe (*a* and *b*) is depicted by the purple dotted line, and a European climate club including border adjustment by the dashed blue line.

Figure 6: Carbon pricing in *a* only (Germany vs. Spain)



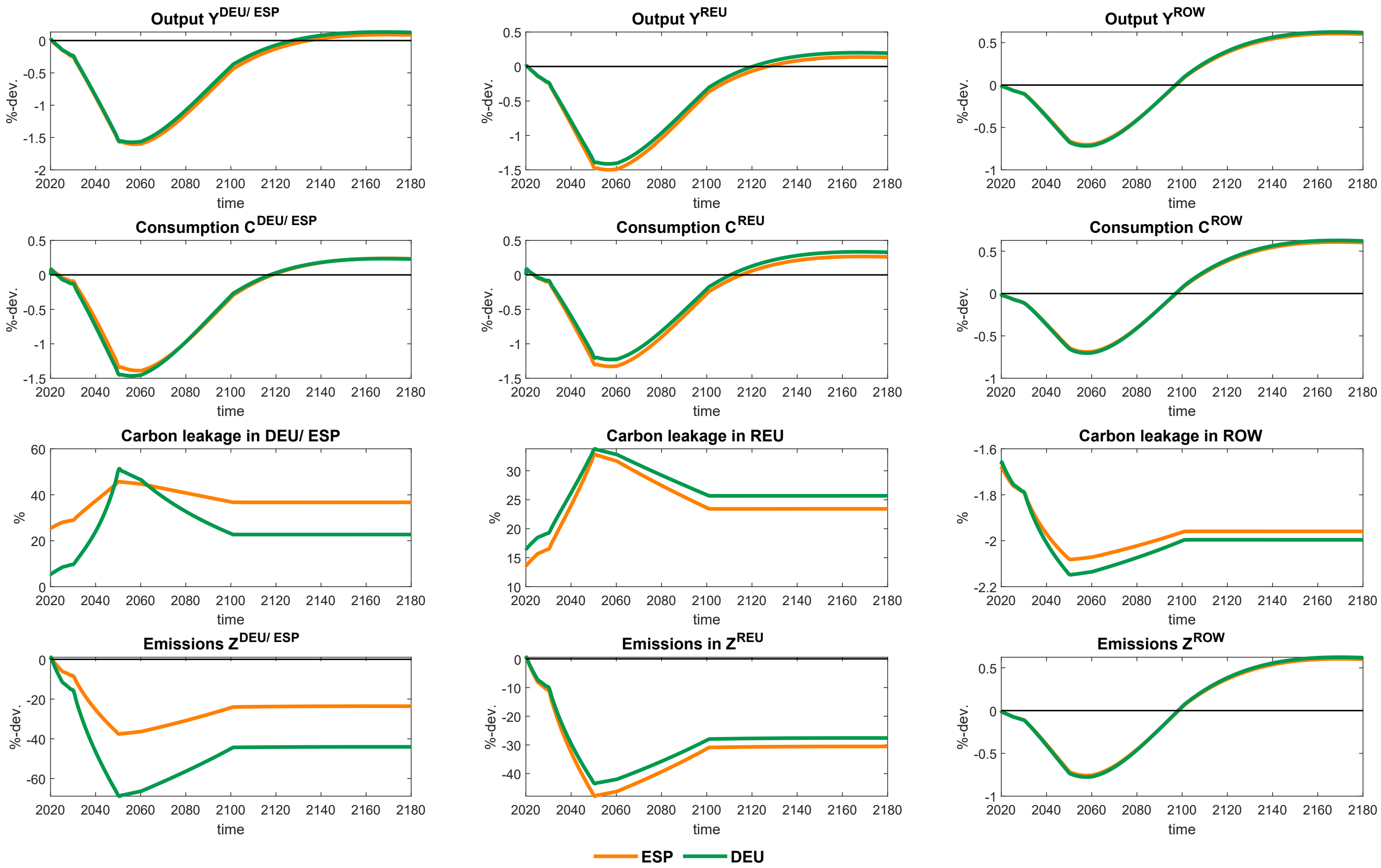
Notes: Figure plots (projected) implications of carbon pricing in *a* only for selected variables in the three regions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure 7: Carbon pricing in *a* and *b* (Germany vs. Spain)



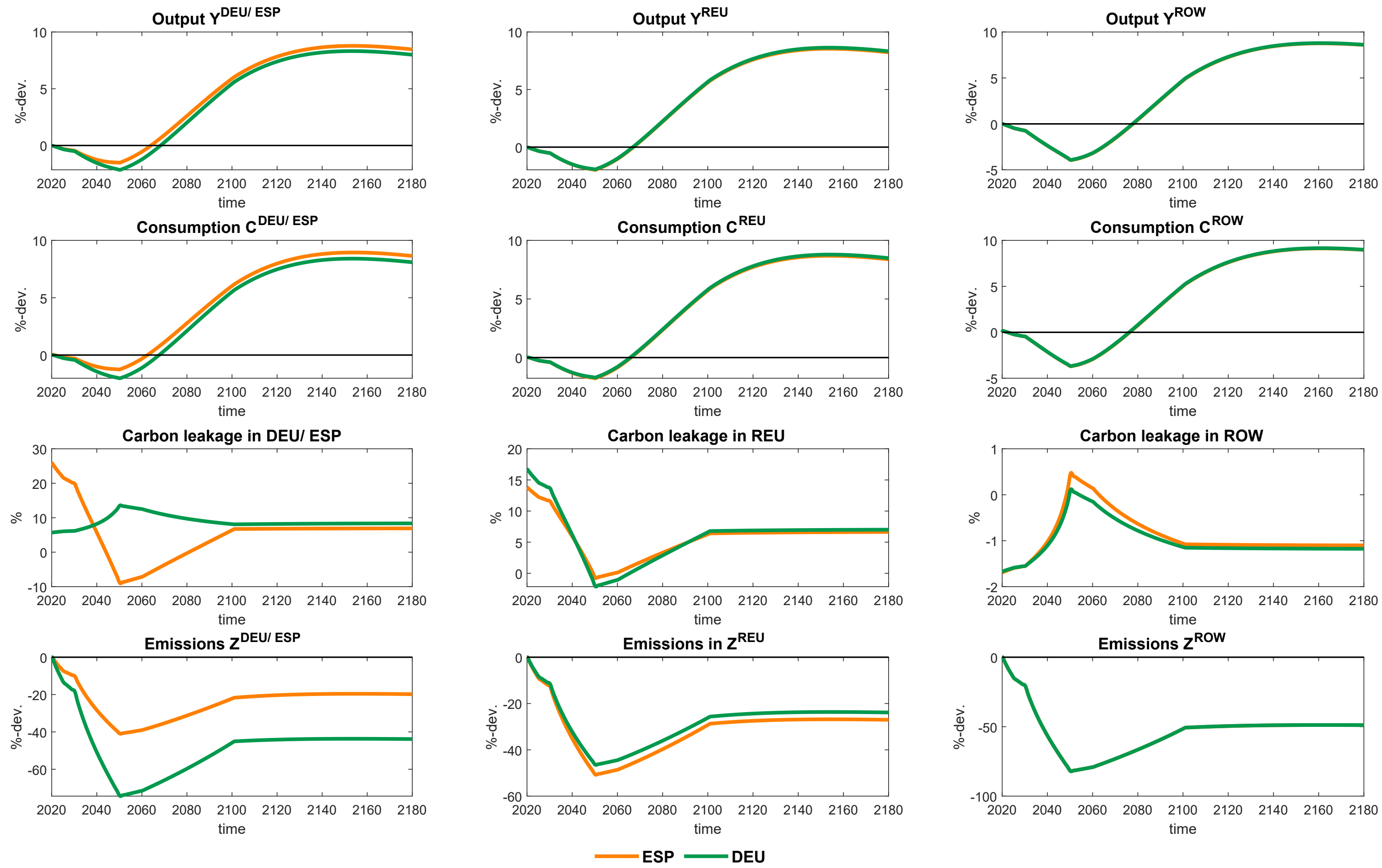
Notes: Figure plots (projected) implications of carbon pricing in *a* and *b* for selected variables in the three regions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure 8: Carbon pricing in *a* and *b* plus border adjustment (Germany vs. Spain)



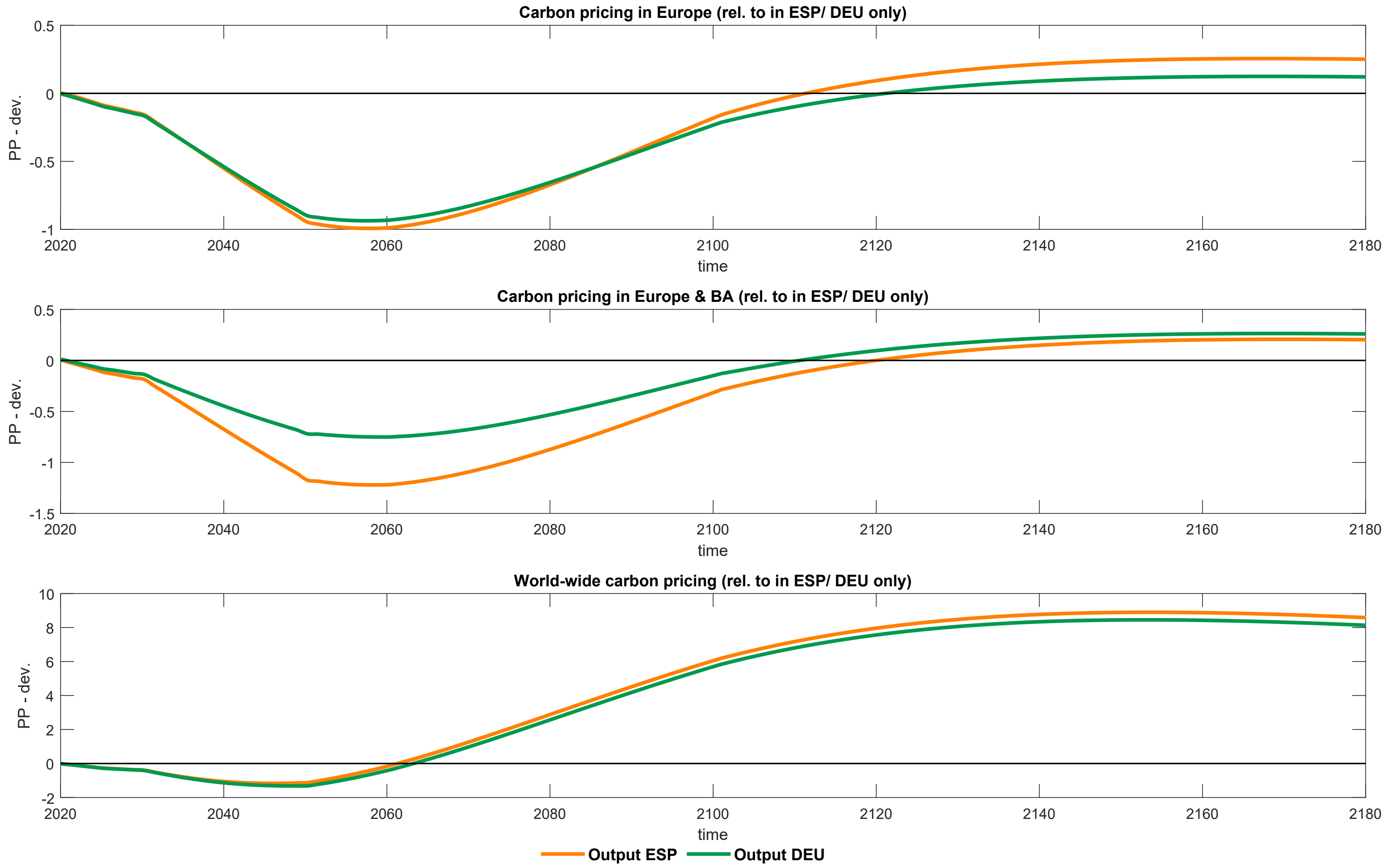
Notes: Figure plots (projected) implications of carbon pricing in *a* and *b* plus border adjustment vis-a-vis *c* for selected variables in the three regions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure 9: World-wide carbon pricing (Germany vs. Spain)



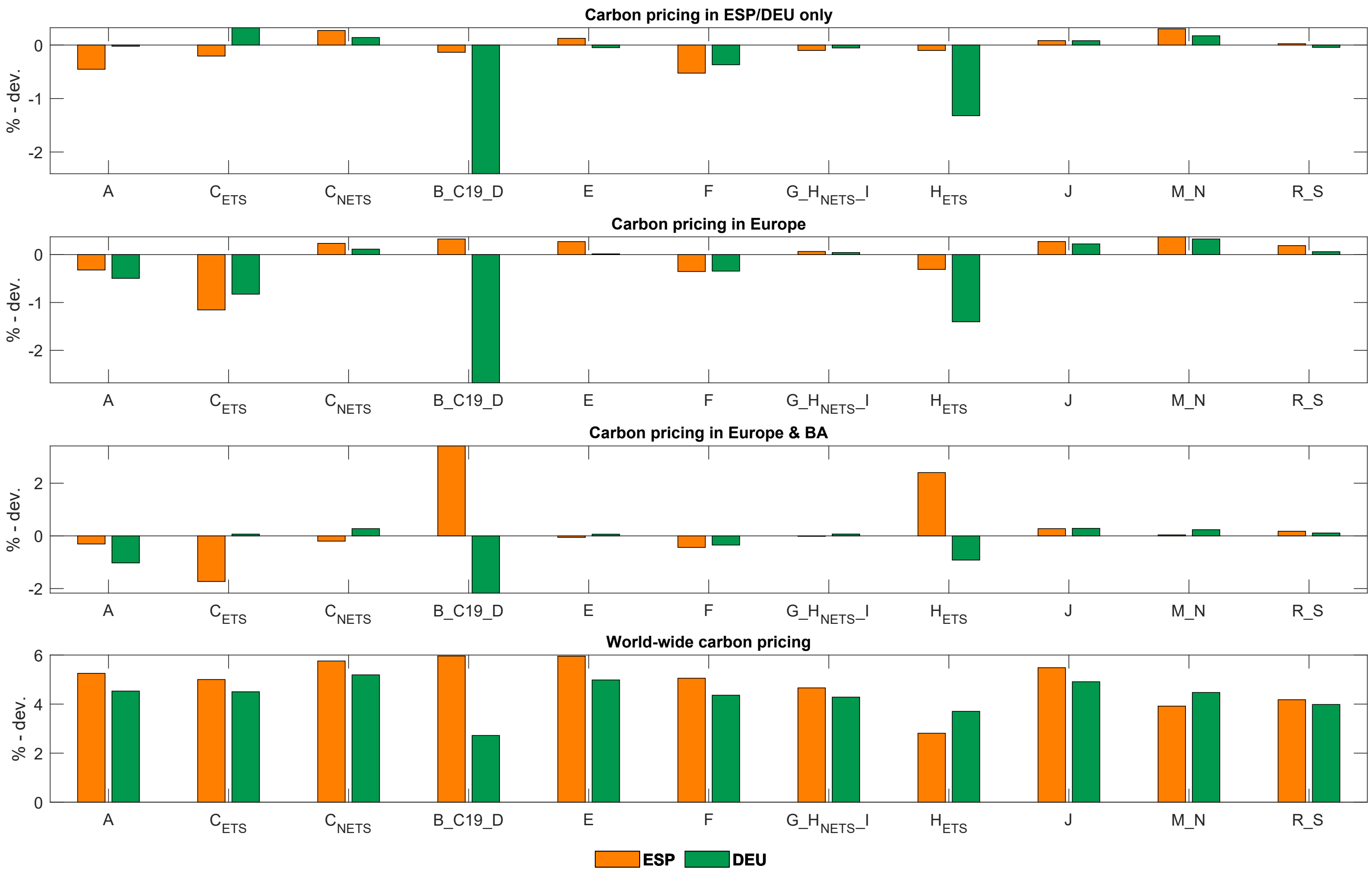
Notes: Figure plots (projected) implications of global carbon pricing for selected variables in the three regions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure 10: Carbon pricing scenarios relative to first scenario (Germany vs. Spain)



Notes: Figure plots (projected) implications of different carbon pricing scenarios relative to the one where only region a introduces the price for selected variables in the three regions. The green lines refer to the calibration with Germany being region a. Orange lines indicate the calibration for Spain.

Figure 11: Long-run changes in sectoral value added implied by carbon pricing



Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for Germany (green bars) and Spain (orange bars). Scenarios are according to headline.

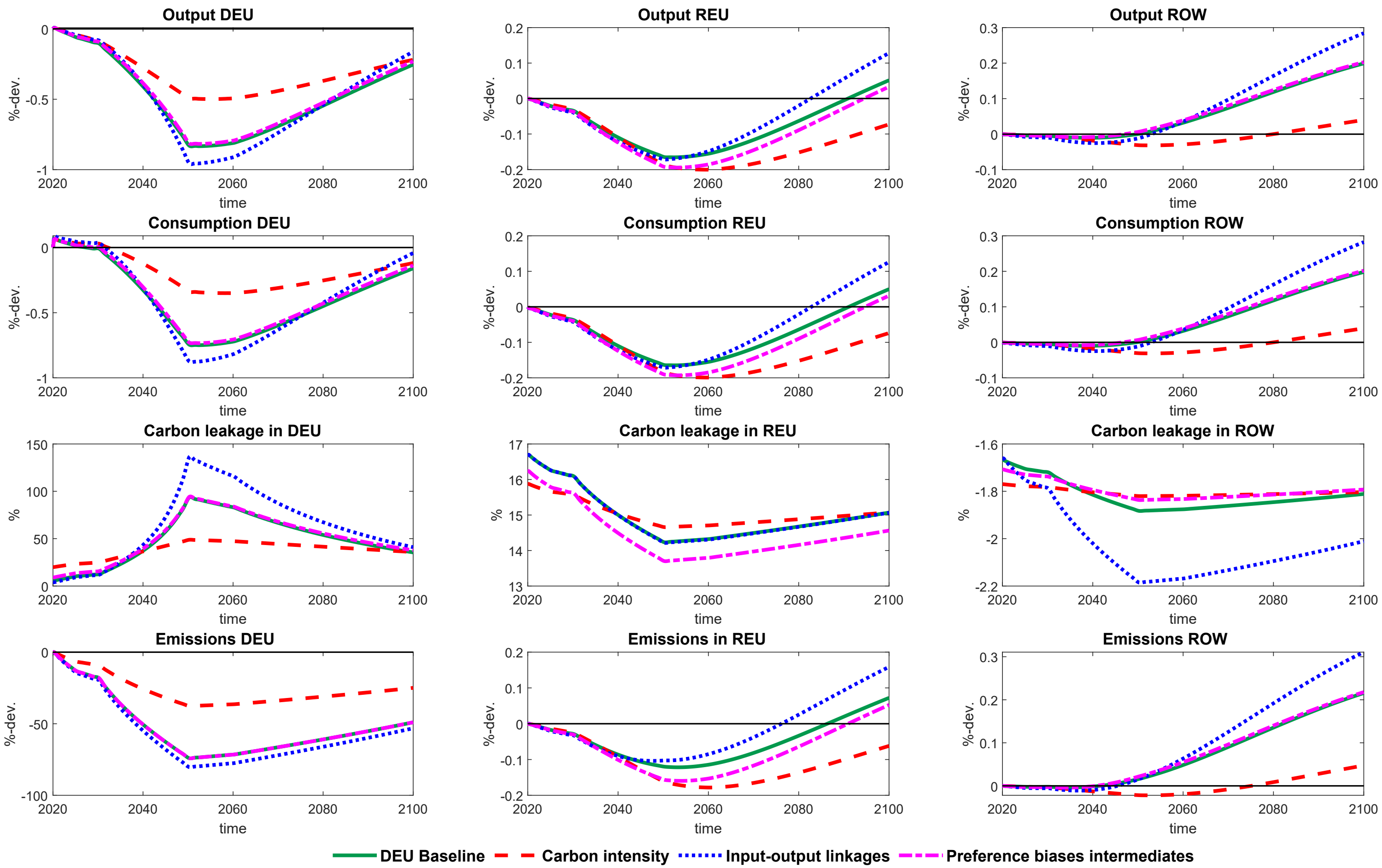
6. Discussion

The results of the previous section show that carbon pricing and border adjustment taxes might affect countries differently depending on their economies' structural characteristics. To investigate the impact of different heterogeneities across regions, we perform several counterfactual simulations. Starting off with the calibration for Germany, we change one dimension of heterogeneity at a time. First, we assume that Germany's production sectors have the same carbon intensities as in Spain. Second, we impose the same inter-sectoral linkages $\psi_{H,s,j,i}$. Third, we take the Spanish preference biases for intermediate inputs ($hb_{H,s,j,ESP,\bar{i}}$). Figure 12 summarizes the results for the first policy scenario where only Germany introduces carbon pricing. Figure 13 presents the same counterfactual results for the climate club scenario with border adjustment vis-a-vis the rest of the world.

Regarding the first scenario, we observe that the drops in output and consumption are less pronounced assuming the Spanish carbon intensities. As these are smaller now compared to the baseline calibration for Germany, so are the transition costs of carbon pricing. Carbon leakage is a minor issue. While the preference biases for intermediate inputs have almost no effect in the scenario where only Germany introduces carbon pricing, the input-output linkages do. Compared to the baseline calibration, the Spanish sectoral relations lead to a more detrimental impact of carbon pricing. One reason is that three out of the four dirtiest sectors depend more on inputs from themselves in Spain than in Germany. This can be seen in Table A.4, comparing $\psi_{H,s,s,a}$ for $s \in \{1, 4, 8\}$. As the carbon price hits especially emission-intensive sectors, they suffer twice - once directly and once indirectly via more expensive intermediate inputs from themselves. Additionally, dirty sectors have also on average larger shares in the sectoral intermediate input bundles in Spain (comparing $\sum_{j\in\{1,2,4,8\}} \psi_{H,s,j,a}$ for $a = DEU/ESP$). This means that the demand for intermediate inputs from ETS sectors is larger in Spain than in Germany.
Figure 13 further illustrates that if Germany had the same preference biases for intermediates as Spain, it would experience larger output and consumption reductions in a European climate club scenario. As Spain imports larger shares of dirty intermediate inputs than Germany (comparing $\sum_{j\in\{2,4,8\}} hb_{H,s,j,a,c}$ for $a = DEU/ESP$), the border adjustment mechanism makes imports relatively more expensive.

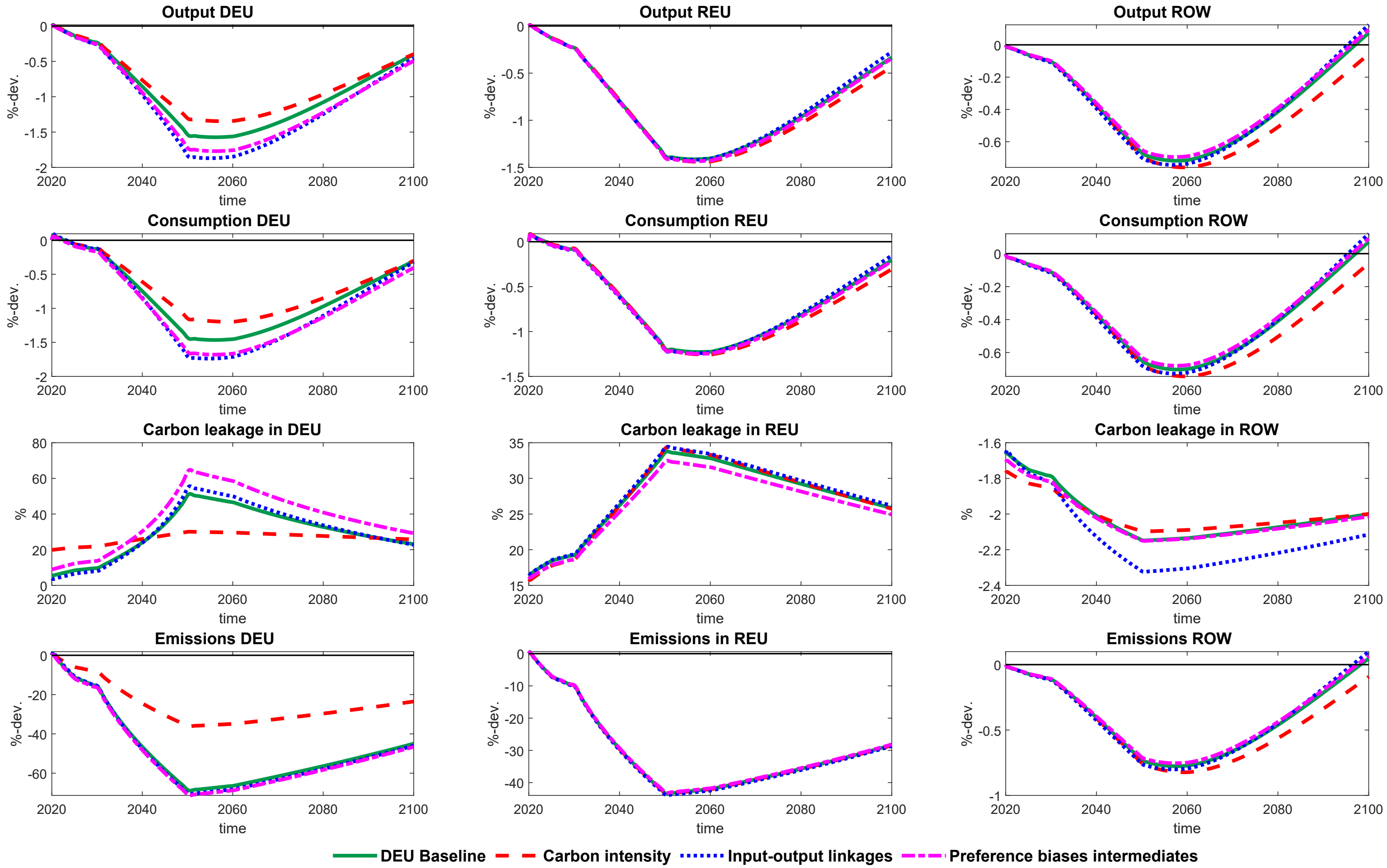
When interpreting and discussing the results, reflecting on the caveats of the analysis is warranted. First, given data limitations, parameters of the damage and abatement cost functions are assumed to be homogenous across Spain, Germany and the rest of Europe. Appendix B provides simulation results for the extreme case without any damage from emissions. As can be seen there, it shuts off the positive productivity effect from world-wide emissions reduction, leading to a permanent negative output effect of carbon pricing. If we e.g. assume that environmental damage from emissions is larger in Spain than in Germany, it would increase the differences between both model calibrations with larger benefits form carbon pricing in Spain. The same holds true for abatement costs. If these are cheaper in one of the regions, relative simulation results would change in favour of this region. However, more disaggregated data on the sectoral as well as regional level is necessary for a clearer picture. Qualitatively, the described transmission channels remain the same though. Second, emissions are directly linked to output and there is only one energy sector in the model. While our model allows sectors to substitute away from dirty intermediate inputs, it could be interesting to additionally consider green and brown energy inputs as well as a direct link between brown energy input and emissions as in Hinterlang et al. (2022). Another related caveat

Figure 12: Carbon pricing in a: Impact of regional heterogeneities



Notes: Figure plots (projected) implications of carbon pricing in a only for selected variables in the three regions. The green lines refer to the baseline calibration with Germany being region a. Red lines refer to the German calibration with Spanish carbon intensities. In the blue counterfactual, we take Spanish input-output linkages. Purple lines indicate Spanish preference biases for intermediate inputs.

Figure 13: Carbon pricing in a and b plus border adjustment: Impact of regional heterogeneities



Notes: Figure plots (projected) implications of carbon pricing in a and b plus border adjustment vis-a-vis c for selected variables in the three regions. The green lines refer to the baseline calibration with Germany being region a. Red lines refer to the German calibration with Spanish carbon intensities. In the blue counterfactual, we take Spanish input-output linkages. Purple lines indicate Spanish preference biases for intermediate inputs.

is that the analysis abstracts from any technological progress, which might accelerate the transition to the final steady state and affect its level. Moreover, carbon revenues are redistributed lump-sum to households in the analysis. Alternative recycling options like labor tax reductions or green subsidies might mitigate the contraction and lower emissions further. Finally, effects might be heterogenous across different types of households as pointed out by (see e.g. Känzig, 2023). All of these points are left for future research.

7. Conclusions

This paper analyzes different climate policy scenarios and contrasts their effects on the German and Spanish economy. In particular, it mirrors the setup of Ernst et al. (2023) to study the effects of carbon pricing and border adjustment in these countries. For this purpose, it relies on the same three-region version of the **e**nvironmental **mu**lti-**se**ctor dynamic general equilibrium model *EMuSe*, calibrated once for Germany, the rest of Europe and the rest of the world and once for Spain with the same counterparts.

The general findings of Ernst et al. (2023) can be confirmed. Carbon pricing leads to a long-lasting downturn of output due to an increase in marginal production costs. At the same time, emissions are reduced, leading to productivity gains through less economic damage. If the second effect is strong enough, long-run output effects are positive. Moreover, there is evidence for carbon leakage, which can be mitigated by a border adjustment mechanism. However, the effects are rather limited as it protects mainly dirty domestic sectors, leading to a rather small additional emissions reduction. All regions benefit in the long run under a global carbon pricing scenario.

In addition, there are also interesting results different from the ones of Ernst et al. (2023). First, when modelling individual countries like Germany and Spain instead of larger regions, it might no longer be true that (small and interlinked) regions introducing carbon pricing benefit from others joining them. Indeed, Germany and Spain face higher transition costs if the rest of Europe follows the same carbon price path. This is because carbon pricing reduces demand further and imports become more expensive. In this scenario, the positive effect of the damage-productivity channel only pays off in the long run. Moreover, while border adjustment was found to be beneficial for Europe as a whole, this might not be the case for individual countries. While Germany gains from border adjustment, countries that depend more on relatively dirty imports from the rest of the world, like Spain, might actually lose due to the additional import tax.

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Appendix

In the appendix, we provide more details on the model calibration (Appendix A) and additional simulation results (Appendix B).

Appendix A: Calibration details

In this Appendix, we provide tables with detailed calibration parameters.

Table A.1: Baseline calibration of general parameters

Variable/Parameter	Symbol	Value
Relative population size, region $a = DEU$	ω^a	0.011
Relative population size, region b	ω^b	0.057
Relative population size, region c	ω^c	0.933
Relative population size, region $a = ESP$	ω^a	0.006
Relative population size, region b	ω^b	0.062
Relative population size, region c	ω^c	0.933
Relative value-added-per-capita, region $a = DEU$		1
Relative value-added-per-capita, region b		0.774
Relative value-added-per-capita, region c		0.167
Relative value-added-per-capita, region $a = ESP$		1
Relative value-added-per-capita, region b		1.235
Relative value-added-per-capita, region c		0.250
Discount factor	β	0.985
Inverse of elasticity of intertemporal substitution	σ	1.000
Inverse of Frisch elasticity of lab. supply	ζ	2.000
Labor disutility scaling	$\kappa_{DEU,N}$	1.877
	$\kappa_{b,N}$	1.847
	$\kappa_{c,N}$	1.721
	$\kappa_{ESP,N}$	1.829
	$\kappa_{b,N}$	1.830
	$\kappa_{c,N}$	1.735
Capital depreciation rate	δ^k	0.025
Capital adjustment costs	κ^I	25
Consumption tax rate	$\bar{\tau}_i^c$	0.200
AR(1) coefficients	ρ^x	0.8
Substitution elasticities:		
Elasticity of substitution, consumption	σ_C	1-1/0.9091
Elasticity of substitution, investment	σ_I	1-1/0.7511
Elasticity of substitution, labor	ν_N	2
Elasticity of substitution, capital	ν_K	2
Elasticity of substitution, intermediates	$\sigma_{H,z}$	1-1/0.3

Notes: The table shows calibrated values for general parameters as described in the main text.

Table A.2: Calibration of sector-specific parameters

	$\alpha_{N,s,i}$	$\alpha_{H,s,i}$	$\omega_{N,s,i}$	$\omega_{K,s,i}$	$\psi_{C,s,i}$	$\psi_{I,s,i}$	$\alpha_{N,s,i}$	$\alpha_{H,s,i}$	$\omega_{N,s,i}$	$\omega_{K,s,i}$	$\psi_{C,s,i}$	$\psi_{I,s,i}$
	Region $i = a$ (DEU)						Region $i = a$ (ESP)					
1) Agriculture	0.788	0.339	0.022	0.054	0.026	0.002	0.311	0.527	0.057	0.038	0.061	0.008
2) MF (ETS)	0.616	0.283	0.034	0.050	0.034	0.008	0.567	0.206	0.024	0.036	0.038	0.005
3) MF (N-ETS)	0.659	0.361	0.216	0.210	0.217	0.457	0.606	0.278	0.131	0.111	0.153	0.251
4) Energy composite	0.365	0.270	0.011	0.071	0.054	0.008	0.245	0.186	0.008	0.102	0.028	0.003
5) Water supply	0.419	0.472	0.009	0.100	0.011	0.000	0.489	0.421	0.012	0.041	0.007	0.001
6) Constr.	0.777	0.437	0.081	0.017	0.009	0.360	0.603	0.418	0.074	0.236	0.018	0.581
7) Trade, transp. (N-ETS), accom., food	0.729	0.517	0.324	0.212	0.420	0.053	0.660	0.557	0.422	0.248	0.522	0.063
8) Transport (ETS)	0.430	0.276	0.003	0.023	0.017	0.000	0.653	0.285	0.004	0.009	0.009	0.001
9) IT and communication	0.577	0.532	0.041	0.041	0.095	0.057	0.526	0.500	0.035	0.058	0.060	0.037
10) Prof./ scient./ techn., admin./ support serv.	0.648	0.599	0.188	0.143	0.034	0.052	0.830	0.574	0.162	0.060	0.036	0.049
11) Arts, entertainm., recreation, oth. serv.	0.666	0.677	0.072	0.078	0.083	0.003	0.779	0.610	0.073	0.060	0.070	0.002
	Region $i = b$ (Rest of EU27, CHE, NOR, UK)											
1) Agriculture	0.788	0.339	0.022	0.054	0.026	0.002	0.707	0.410	0.070	0.063	0.045	0.004
2) MF (ETS)	0.616	0.283	0.034	0.050	0.034	0.008	0.601	0.252	0.026	0.043	0.038	0.006
3) MF (N-ETS)	0.659	0.361	0.216	0.210	0.217	0.457	0.625	0.331	0.174	0.168	0.182	0.337
4) Energy composite	0.365	0.270	0.011	0.071	0.054	0.008	0.275	0.306	0.014	0.118	0.052	0.005
5) Water supply	0.419	0.472	0.009	0.100	0.011	0.000	0.475	0.409	0.010	0.055	0.008	0.000
6) Constr.	0.777	0.437	0.081	0.017	0.009	0.360	0.760	0.385	0.090	0.064	0.012	0.430
7) Trade, transp. (N-ETS), accom., food	0.729	0.517	0.324	0.212	0.420	0.053	0.671	0.510	0.335	0.251	0.451	0.083
8) Transport (ETS)	0.430	0.276	0.003	0.023	0.017	0.000	0.537	0.274	0.005	0.017	0.022	0.001
9) IT and communication	0.577	0.532	0.041	0.041	0.095	0.057	0.601	0.504	0.041	0.057	0.083	0.073
10) Prof./ scient./ techn., admin./ support serv.	0.648	0.599	0.188	0.143	0.034	0.052	0.717	0.548	0.174	0.116	0.036	0.055
11) Arts, entertainm., recreation, oth. serv.	0.666	0.677	0.072	0.078	0.083	0.003	0.731	0.585	0.062	0.049	0.072	0.006
	Region $i = c$ (ROW)											
1) Agriculture	0.773	0.584	0.329	0.059	0.076	0.004						
2) MF (ETS)	0.414	0.222	0.031	0.082	0.033	0.005						
3) MF (N-ETS)	0.523	0.262	0.153	0.203	0.143	0.309						
4) Energy composite	0.272	0.368	0.020	0.197	0.047	0.009						
5) Water supply	0.627	0.497	0.001	0.017	0.004	0.000						
6) Constr.	0.714	0.355	0.099	0.026	0.001	0.466						
7) Trade, transp. (N-ETS), accom., food	0.568	0.581	0.242	0.178	0.468	0.080						
8) Transport (ETS)	0.500	0.370	0.005	0.020	0.023	0.002						
9) IT and communication	0.470	0.567	0.019	0.091	0.069	0.068						
10) Prof./ scient./ techn., admin./ support serv.	0.692	0.571	0.038	0.055	0.044	0.056						
11) Arts, entertainm., recreation, oth. serv.	0.760	0.559	0.062	0.071	0.093	0.001						

Notes: The table shows calibrated values for sector-specific parameters as described in the main text for the model version with either Germany or Spain as individual country a. The values were computed by the authors based on the World Input-Output Database for the year 2014.

Table A.3: Preference biases, consumption and investment, $hb_{X,s,i,\bar{i}}$

	Region $i = a$ (DEU)						Region $i = a$ (ESP)					
	$hb_{C,s,a,a}$	$hb_{C,s,a,b}$	$hb_{C,s,a,c}$	$hb_{I,s,a,a}$	$hb_{I,s,a,b}$	$hb_{I,s,a,c}$	$hb_{C,s,a,a}$	$hb_{C,s,a,b}$	$hb_{C,s,a,c}$	$hb_{I,s,a,a}$	$hb_{I,s,a,b}$	$hb_{I,s,a,c}$
1) Agriculture	0.441	0.448	0.111	0.981	0.018	0.002	0.855	0.120	0.025	0.916	0.037	0.047
2) MF (ETS)	0.756	0.204	0.040	0.888	0.102	0.009	0.838	0.141	0.021	0.913	0.069	0.018
3) MF (N-ETS)	0.642	0.233	0.125	0.590	0.268	0.143	0.596	0.313	0.091	0.431	0.474	0.095
4) Energy composite	0.895	0.039	0.066	0.976	0.015	0.010	0.990	0.006	0.004	0.987	0.008	0.004
5) Water supply	0.900	0.000	0.100	0.983	0.009	0.008	0.999	0.001	0.000	0.995	0.004	0.002
6) Constr.	0.886	0.014	0.100	1.000	0.001	-0.000	0.997	0.002	0.001	1.000	0.000	0.000
7) Trade, transp. (N-ETS), accom., food	0.948	0.030	0.022	0.912	0.064	0.024	0.973	0.018	0.009	0.928	0.067	0.005
8) Transport (ETS)	0.896	0.060	0.044	0.713	0.151	0.136	0.465	0.293	0.242	0.939	0.026	0.036
9) IT and communication	0.868	0.056	0.077	0.926	0.021	0.053	0.934	0.040	0.026	0.921	0.029	0.051
10) Prof./ scient./ techn., admin./ support serv.	0.946	0.031	0.023	0.980	0.013	0.007	0.824	0.116	0.060	0.995	0.003	0.002
11) Arts, entertainm., recreation, oth. serv.	0.985	0.011	0.004	0.955	0.037	0.008	0.907	0.050	0.042	0.962	0.030	0.008

	Region $i = b$ (Rest of EU27, CHE, NOR, UK)											
	$hb_{C,s,b,a}$	$hb_{C,s,b,b}$	$hb_{C,s,b,c}$	$hb_{I,s,b,a}$	$hb_{I,s,b,b}$	$hb_{I,s,b,c}$	$hb_{C,s,b,a}$	$hb_{C,s,b,b}$	$hb_{C,s,b,c}$	$hb_{I,s,b,a}$	$hb_{I,s,b,b}$	$hb_{I,s,b,c}$
1) Agriculture	0.007	0.919	0.074	0.004	0.991	0.005	0.021	0.874	0.105	0.000	0.946	0.054
2) MF (ETS)	0.040	0.899	0.061	0.025	0.923	0.052	0.013	0.941	0.046	0.006	0.952	0.042
3) MF (N-ETS)	0.080	0.754	0.166	0.123	0.700	0.177	0.029	0.827	0.145	0.022	0.822	0.156
4) Energy composite	0.010	0.981	0.010	0.004	0.976	0.020	0.001	0.977	0.022	0.000	0.983	0.017
5) Water supply	0.001	0.898	0.101	0.004	0.989	0.006	0.000	1.000	0.000	0.000	0.994	0.005
6) Constr.	0.002	0.979	0.019	0.001	0.999	0.000	0.000	0.981	0.018	0.000	1.000	0.000
7) Trade, transp. (N-ETS), accom., food	0.007	0.970	0.023	0.018	0.974	0.008	0.002	0.974	0.024	0.000	0.989	0.011
8) Transport (ETS)	0.016	0.857	0.127	0.008	0.943	0.049	0.020	0.871	0.109	0.002	0.943	0.054
9) IT and communication	0.012	0.941	0.047	0.008	0.959	0.034	0.003	0.942	0.055	0.001	0.962	0.036
10) Prof./ scient./ techn., admin./ support serv.	0.012	0.911	0.077	0.008	0.976	0.016	0.017	0.915	0.068	0.002	0.984	0.015
11) Arts, entertainm., recreation, oth. serv.	0.003	0.965	0.032	0.000	0.995	0.004	0.004	0.971	0.025	0.001	0.995	0.005

	Region $i = c$ (ROW)											
	$hb_{C,s,c,a}$	$hb_{C,s,c,b}$	$hb_{C,s,c,c}$	$hb_{I,s,c,a}$	$hb_{I,s,c,b}$	$hb_{I,s,c,c}$	$hb_{C,s,c,a}$	$hb_{C,s,c,b}$	$hb_{C,s,c,c}$	$hb_{I,s,c,a}$	$hb_{I,s,c,b}$	$hb_{I,s,c,c}$
1) Agriculture	0.008	0.009	0.983	0.008	0.009	0.983	0.000	0.019	0.980	0.000	0.019	0.980
2) MF (ETS)	0.000	0.029	0.971	0.000	0.029	0.971	0.005	0.024	0.971	0.005	0.024	0.971
3) MF (N-ETS)	0.002	0.042	0.956	0.002	0.042	0.956	0.005	0.039	0.956	0.005	0.039	0.956
4) Energy composite	0.006	0.021	0.973	0.006	0.021	0.973	0.005	0.024	0.971	0.005	0.024	0.971
5) Water supply	0.004	0.022	0.973	0.004	0.022	0.973	0.000	0.003	0.996	0.000	0.003	0.996
6) Constr.	0.000	0.002	0.997	0.000	0.002	0.997	0.000	0.002	0.998	0.000	0.002	0.998
7) Trade, transp. (N-ETS), accom., food	0.002	0.010	0.988	0.002	0.010	0.988	0.001	0.012	0.987	0.001	0.012	0.987
8) Transport (ETS)	0.004	0.034	0.962	0.004	0.034	0.962	0.000	0.039	0.960	0.000	0.039	0.960
9) IT and communication	0.006	0.013	0.981	0.006	0.013	0.981	0.000	0.020	0.980	0.000	0.020	0.980
10) Prof./ scient./ techn., admin./ support serv.	0.002	0.022	0.976	0.002	0.022	0.976	0.002	0.023	0.975	0.002	0.023	0.975
11) Arts, entertainm., recreation, oth. serv.	0.001	0.007	0.992	0.001	0.007	0.992	0.001	0.007	0.992	0.001	0.007	0.992

Notes: This table reports parameter values for the sector-specific preference biases $hb_{X,s,i,\bar{i}}$, $X \in C, I$ of region i towards goods produced in region $\bar{i}$ for the model calibration with Germany or Spain as individual region a. These were computed based on the World Input-Output Database for the year 2014. Parameters for region $i = c$ were used to close the model. Hence, home biases of this region might slightly differ across both model calibrations.

Table A.4: Input-Output matrix, $\psi_{H,s,j,i}$

	Consumer s																					
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
	Region $i = a$ (DEU)											Region $i = a$ (ESP)										
1)	14.9	0.3	0.4	0.2	0.1	0.1	0.6	0.1	0.0	0.3	0.4	23.8	1.4	0.8	0.1	0.1	0.2	3.7	0.2	0.2	0.2	1.1
2)	16.3	48.4	14.4	5.4	5.3	19.8	2.6	1.9	1.7	1.9	3.4	11.2	37.5	22.0	6.5	12.7	18.0	5.3	1.3	7.1	4.9	5.4
3)	12.4	10.6	55.5	17.4	18.0	35.8	10.7	13.4	18.1	5.2	9.6	19.5	15.5	49.7	13.7	23.6	19.7	15.9	23.6	22.0	18.5	21.3
4)	4.3	8.3	1.7	34.6	17.8	1.4	3.1	0.5	1.1	1.5	3.6	6.4	13.3	2.4	47.1	17.6	1.6	6.9	1.3	2.2	3.1	3.4
5)	0.8	0.6	0.1	0.8	0.9	0.1	0.3	0.0	0.1	0.2	1.1	2.7	0.4	0.1	2.4	14.8	0.1	0.7	0.2	0.2	0.4	1.0
6)	2.3	1.2	0.8	7.6	13.5	13.9	2.7	0.6	1.9	2.3	3.6	1.2	1.5	0.9	2.5	2.1	43.0	3.6	0.8	2.2	3.4	4.4
7)	18.7	15.2	13.6	14.3	11.1	15.0	52.3	56.9	10.3	5.7	10.1	29.2	22.2	16.3	13.0	13.0	8.7	41.1	35.5	12.0	17.9	16.9
8)	0.3	0.6	0.4	0.7	0.3	0.2	1.0	2.1	0.7	0.9	0.9	0.1	0.3	0.2	0.2	0.2	0.1	1.0	12.0	0.2	4.0	1.4
9)	0.7	1.7	1.8	2.3	5.4	1.4	5.8	0.9	43.9	15.7	8.2	0.9	1.9	1.7	4.8	3.3	1.0	5.5	4.4	38.6	10.4	9.2
10)	28.4	12.6	10.7	15.6	25.8	11.7	19.3	23.3	16.7	63.1	18.0	4.6	5.6	5.6	9.3	12.4	7.5	15.3	20.5	13.2	35.0	16.3
11)	0.7	0.6	0.4	1.2	1.9	0.6	1.6	0.3	5.3	3.2	41.1	0.3	0.3	0.3	0.4	0.2	0.1	1.0	0.2	2.2	2.2	19.6
	Region $i = b$ (Rest of EU27, CHE, NOR, UK)																					
1)	38.8	1.2	0.8	0.3	0.2	0.3	1.7	0.2	0.1	0.3	0.7	37.0	1.0	0.7	0.3	0.2	0.2	1.4	0.2	0.1	0.4	0.6
2)	12.4	41.8	15.9	5.2	7.8	15.2	3.4	2.1	4.0	3.0	4.2	12.9	43.8	15.1	5.1	6.9	15.7	3.1	2.1	3.4	2.7	4.0
3)	10.8	12.0	48.6	9.8	15.3	23.9	11.7	13.4	17.3	11.2	13.3	10.4	11.3	50.5	10.6	14.6	26.4	11.2	13.0	17.1	9.6	12.0
4)	4.3	10.8	2.0	56.6	23.3	1.8	3.5	1.1	1.7	1.6	5.0	4.1	10.0	1.9	54.0	23.2	1.8	3.2	1.0	1.6	1.5	4.8
5)	0.8	0.3	0.1	1.1	10.8	0.1	0.2	0.1	0.1	0.1	0.6	0.7	0.4	0.1	1.0	8.8	0.1	0.2	0.1	0.1	0.1	0.7
6)	1.7	1.0	0.9	3.3	7.1	31.5	3.6	1.7	1.9	2.2	3.6	1.9	1.1	0.9	4.0	8.7	27.2	3.5	1.6	1.9	2.2	3.6
7)	23.5	22.5	18.0	12.3	12.4	12.5	43.4	46.6	14.5	15.2	16.9	22.5	20.7	16.8	12.5	12.1	13.3	45.2	48.5	13.9	13.2	15.4
8)	0.3	0.5	0.4	0.7	0.3	0.2	2.0	11.8	0.6	2.7	1.1	0.3	0.6	0.4	0.7	0.3	0.2	1.9	10.4	0.7	2.3	1.1
9)	1.1	1.5	2.2	2.3	5.1	1.8	7.2	4.4	32.5	12.6	11.5	1.0	1.6	2.2	2.2	5.4	1.9	7.1	3.9	34.2	13.3	10.9
10)	5.7	7.8	10.5	7.8	16.0	12.0	21.7	17.6	24.2	49.0	25.7	8.6	9.2	10.9	8.8	17.8	12.5	21.7	18.3	23.4	52.5	24.6
11)	0.7	0.4	0.5	0.6	1.7	0.6	1.5	1.0	3.0	2.0	17.4	0.7	0.5	0.5	0.7	1.9	0.6	1.5	0.9	3.5	2.2	22.5
	Region $i = c$ (ROW)																					
1)	44.8	1.1	1.4	0.2	0.1	2.6	3.7	0.1	0.0	0.2	0.8											
2)	13.6	43.7	19.6	5.4	5.7	23.3	3.8	1.9	3.0	3.3	7.7											
3)	7.9	11.0	51.9	12.6	9.7	31.9	19.2	16.4	14.8	14.1	19.4											
4)	6.2	18.1	3.1	42.6	40.9	4.3	7.2	2.9	2.4	3.3	8.4											
5)	0.3	0.4	0.1	1.3	14.5	0.2	0.6	0.3	0.2	0.4	1.3											
6)	1.1	0.7	0.4	3.2	8.4	4.4	2.0	0.5	1.2	1.1	2.7											
7)	21.4	16.2	13.9	18.5	10.8	20.3	31.9	35.3	12.0	17.3	23.0											
8)	1.5	2.0	1.0	3.1	0.8	1.2	2.2	18.8	1.0	2.2	2.5											
9)	0.5	1.0	1.7	2.2	2.5	2.8	7.2	4.7	35.3	18.5	7.4											
10)	2.2	4.9	6.2	9.5	5.3	8.1	20.0	18.6	26.6	36.3	15.6											
11)	0.5	0.7	0.5	1.3	1.3	0.7	2.3	0.7	3.5	3.2	11.2											

Notes: This table reports the share of total intermediates (in expenditure terms and %) used by the consuming sector that comes from the producing sector for the model calibration with Germany or Spain as individual region a. (For example, 14.4% of the total intermediates used by the third sector stem from the second sector in region $i = DEU$.) The shares were computed by the authors based on the World Input-Output Database for the year 2014.

Table A.5: Preference biases, intermediate inputs, $hb_{H,s,j,i,\bar{i}}$

	Consumer s																					
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
	Region $i = a$ (DEU)											Region $i = a$ (ESP)										
	Region $\bar{i} = a$ (DEU)											Region $\bar{i} = a$ (ESP)										
1)	0.792	0.782	0.801	0.763	0.765	0.805	0.774	0.842	0.865	0.835	0.785	0.860	0.802	0.804	0.861	0.860	0.966	0.874	0.911	0.909	0.883	0.910
2)	0.585	0.578	0.589	0.645	0.626	0.747	0.661	0.551	0.715	0.694	0.672	0.579	0.658	0.679	0.574	0.513	0.849	0.672	0.719	0.676	0.671	0.680
3)	0.758	0.752	0.693	0.816	0.725	0.766	0.795	0.447	0.647	0.812	0.641	0.749	0.763	0.600	0.661	0.620	0.770	0.672	0.587	0.632	0.693	0.773
4)	0.745	0.583	0.689	0.638	0.677	0.653	0.712	0.655	0.756	0.813	0.810	0.978	0.602	0.957	0.639	0.995	0.472	0.977	0.907	0.971	0.969	0.975
5)	0.987	0.966	0.975	0.985	0.956	0.988	0.984	0.740	0.985	0.985	0.998	0.999	0.851	0.975	0.996	1.000	0.987	0.993	0.981	0.991	0.992	0.990
6)	0.985	0.896	0.948	0.965	0.989	0.993	0.990	0.984	0.993	0.989	0.994	0.984	0.966	0.966	0.959	0.977	0.999	0.994	0.978	0.988	0.978	0.995
7)	0.916	0.860	0.898	0.860	0.885	0.910	0.923	0.896	0.911	0.888	0.878	0.940	0.899	0.914	0.850	0.913	0.922	0.929	0.916	0.916	0.902	0.926
8)	0.324	0.461	0.533	0.382	0.583	0.747	0.302	0.465	0.799	0.761	0.794	0.697	0.472	0.570	0.436	0.771	0.649	0.460	0.164	0.487	0.197	0.181
9)	0.871	0.856	0.864	0.871	0.869	0.900	0.891	0.898	0.915	0.888	0.880	0.929	0.942	0.931	0.937	0.915	0.942	0.941	0.933	0.947	0.921	0.922
10)	0.958	0.915	0.910	0.923	0.913	0.944	0.943	0.988	0.941	0.933	0.962	0.671	0.708	0.702	0.707	0.705	0.821	0.737	0.785	0.761	0.712	0.766
11)	0.980	0.967	0.955	0.990	0.985	0.963	0.990	0.959	0.994	0.994	0.999	0.965	0.907	0.927	0.947	0.871	0.892	0.948	0.845	0.970	0.961	0.978
	Region $\bar{i} = b$ (Rest of EU27, CHE, NOR, UK)																					
1)	0.085	0.111	0.098	0.158	0.200	0.109	0.100	0.079	0.102	0.069	0.092	0.062	0.028	0.034	0.055	0.078	0.015	0.057	0.047	0.044	0.080	0.042
2)	0.332	0.345	0.332	0.290	0.298	0.206	0.289	0.425	0.235	0.251	0.261	0.321	0.267	0.255	0.282	0.371	0.115	0.252	0.186	0.278	0.269	0.254
3)	0.189	0.199	0.197	0.127	0.174	0.180	0.132	0.335	0.112	0.111	0.180	0.205	0.199	0.346	0.275	0.327	0.191	0.280	0.300	0.275	0.234	0.176
4)	0.156	0.252	0.202	0.218	0.197	0.212	0.176	0.180	0.151	0.119	0.117	0.009	0.037	0.018	0.030	0.003	0.048	0.013	0.016	0.017	0.023	0.015
5)	0.009	0.027	0.017	0.009	0.034	0.008	0.012	0.160	0.011	0.013	0.002	0.001	0.126	0.022	0.002	0.000	0.010	0.006	0.008	0.007	0.007	0.009
6)	0.013	0.099	0.049	0.033	0.009	0.006	0.008	0.014	0.005	0.009	0.005	0.015	0.019	0.032	0.013	0.022	0.001	0.005	0.017	0.011	0.021	0.004
7)	0.061	0.098	0.068	0.076	0.069	0.060	0.048	0.074	0.045	0.069	0.066	0.045	0.065	0.067	0.053	0.072	0.056	0.047	0.055	0.064	0.063	0.049
8)	0.436	0.342	0.292	0.393	0.260	0.151	0.450	0.340	0.112	0.138	0.114	0.182	0.295	0.243	0.320	0.149	0.197	0.301	0.457	0.291	0.440	0.449
9)	0.064	0.065	0.064	0.051	0.050	0.047	0.050	0.047	0.038	0.046	0.058	0.055	0.040	0.045	0.045	0.049	0.041	0.037	0.040	0.036	0.041	0.040
10)	0.029	0.052	0.055	0.045	0.050	0.035	0.033	0.004	0.033	0.039	0.022	0.259	0.230	0.234	0.229	0.229	0.134	0.198	0.118	0.179	0.226	0.173
11)	0.011	0.015	0.036	0.005	0.005	0.032	0.005	0.014	0.004	0.003	0.000	0.020	0.035	0.047	0.033	0.078	0.065	0.027	0.080	0.014	0.020	0.007
	Region $\bar{i} = c$ (ROW)																					
1)	0.123	0.107	0.101	0.079	0.034	0.086	0.126	0.080	0.033	0.096	0.122	0.077	0.170	0.162	0.083	0.063	0.019	0.069	0.042	0.047	0.036	0.048
2)	0.083	0.078	0.078	0.065	0.076	0.047	0.050	0.023	0.050	0.055	0.068	0.100	0.074	0.066	0.143	0.116	0.036	0.076	0.096	0.046	0.060	0.067
3)	0.054	0.049	0.110	0.057	0.101	0.054	0.072	0.218	0.241	0.077	0.179	0.046	0.037	0.054	0.065	0.054	0.039	0.048	0.113	0.093	0.074	0.051
4)	0.100	0.166	0.109	0.144	0.126	0.135	0.112	0.165	0.093	0.068	0.073	0.014	0.361	0.024	0.331	0.002	0.480	0.011	0.077	0.012	0.008	0.010
5)	0.003	0.007	0.008	0.006	0.010	0.004	0.004	0.100	0.004	0.003	0.001	0.000	0.023	0.003	0.002	0.000	0.003	0.001	0.011	0.001	0.001	0.001
6)	0.002	0.004	0.003	0.002	0.001	0.001	0.002	0.002	0.002	0.003	0.001	0.001	0.015	0.002	0.028	0.001	0.000	0.001	0.005	0.001	0.001	0.001
7)	0.023	0.042	0.034	0.064	0.046	0.030	0.029	0.030	0.044	0.043	0.056	0.015	0.036	0.019	0.096	0.015	0.022	0.024	0.029	0.020	0.035	0.025
8)	0.240	0.198	0.175	0.225	0.156	0.103	0.248	0.195	0.089	0.101	0.091	0.121	0.233	0.187	0.245	0.080	0.154	0.239	0.379	0.221	0.363	0.370
9)	0.065	0.080	0.072	0.078	0.081	0.054	0.060	0.055	0.047	0.065	0.062	0.017	0.018	0.024	0.017	0.036	0.017	0.022	0.027	0.017	0.038	0.038
10)	0.013	0.032	0.035	0.032	0.037	0.020	0.025	0.007	0.026	0.027	0.016	0.070	0.062	0.064	0.064	0.066	0.044	0.065	0.096	0.060	0.061	0.061
11)	0.008	0.018	0.010	0.004	0.010	0.005	0.004	0.027	0.002	0.002	0.000	0.014	0.058	0.027	0.020	0.051	0.044	0.025	0.075	0.016	0.019	0.015
	Region $i = b$ (Rest of EU27, CHE, NOR, UK)																					
	Region $\bar{i} = a$ (DEU)											Region $\bar{i} = a$ (ESP)										
1)	0.010	0.009	0.011	0.009	0.010	0.013	0.008	0.003	0.003	0.009	0.009	0.001	0.003	0.002	0.001	0.004	0.002	0.003	0.003	0.011	0.008	0.005
2)	0.131	0.080	0.104	0.085	0.111	0.055	0.092	0.121	0.081	0.090	0.104	0.018	0.015	0.016	0.012	0.018	0.016	0.012	0.011	0.014	0.013	0.016
3)	0.074	0.072	0.080	0.077	0.089	0.073	0.088	0.064	0.064	0.064	0.068	0.010	0.010	0.013	0.007	0.011	0.010	0.015	0.009	0.005	0.008	0.008
4)	0.031	0.032	0.024	0.017	0.009	0.016	0.030	0.019	0.028	0.024	0.029	0.002	0.002	0.003	0.002	0.001	0.002	0.003	0.002	0.002	0.003	0.002
5)	0.006	0.055	0.024	0.021	0.001	0.015	0.016	0.011	0.014	0.015	0.011	0.000	0.002	0.002	0.000	0.000	0.003	0.002	0.002	0.003	0.008	0.001
6)	0.006	0.012	0.024	0.004	0.003	0.001	0.002	0.005	0.002	0.003	0.002	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
7)	0.012	0.015	0.018	0.009	0.012	0.013	0.005	0.016	0.009	0.009	0.009	0.001	0.002	0.001	0.002	0.003	0.001	0.005	0.014	0.002	0.003	0.002
8)	0.019	0.034	0.026	0.025	0.015	0.017	0.032	0.031	0.022	0.023	0.025	0.017	0.026	0.023	0.029	0.025	0.024	0.030	0.031	0.032	0.031	0.032
9)	0.009	0.007	0.009	0.008	0.008	0.004	0.007	0.005	0.011	0.009	0.008	0.005	0.008	0.006	0.004	0.004	0.004	0.005	0.003	0.003	0.004	0.004
10)	0.007	0.010	0.011	0.011	0.008	0.009	0.009	0.005	0.008	0.010	0.008	0.004	0.007	0.006	0.007	0.007	0.007	0.009	0.004	0.009	0.010	0.011
11)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.000
	Region $\bar{i} = b$																					
1)	0.929	0.872	0.872	0.928	0.913	0.883	0.924	0.951	0.961	0.905	0.920	0.934	0.884	0.887	0.935	0.921	0.887	0.925	0.948	0.954	0.903	0.912
2)	0.747	0.774	0.775	0.800	0.777	0.890	0.822	0.774	0.851	0.831	0.788	0.865	0.873	0.869	0.884	0.876	0.928	0.906	0.894	0.916	0.909	0.880
3)	0.855	0.856	0.784	0.835	0.823	0.858	0.827	0.824	0.795	0.845	0.820	0.917	0.920	0.869	0.910	0.891	0.922	0.899	0.863	0.830	0.901	0.861
4)	0.922	0.764	0.940	0.844	0.956	0.760	0.934	0.917	0.950	0.948	0.948	0.940	0.819	0.940	0.869	0.950	0.811	0.944	0.928	0.966	0.958	0.966
5)	0.992	0.914	0.958	0.939	0.954	0.975	0.966	0.963	0.980	0.971	0.983	0.997	0.977	0.983	0.957	0.946	0.987	0.980	0.968	0.990	0.979	0.994

6)	0.983	0.971	0.967	0.973	0.985	0.987	0.983	0.983	0.987	0.984	0.987	0.989	0.986	0.991	0.983	0.990	0.986	0.986	0.988	0.989	0.987	0.989
7)	0.963	0.941	0.953	0.826	0.959	0.954	0.958	0.862	0.946	0.941	0.954	0.973	0.954	0.968	0.844	0.964	0.966	0.959	0.877	0.952	0.947	0.958
8)	0.846	0.784	0.804	0.769	0.886	0.884	0.792	0.776	0.800	0.767	0.761	0.834	0.791	0.807	0.764	0.867	0.880	0.789	0.784	0.810	0.782	0.789
9)	0.952	0.943	0.938	0.945	0.952	0.951	0.953	0.958	0.950	0.951	0.947	0.952	0.931	0.935	0.940	0.949	0.949	0.951	0.958	0.954	0.950	0.948
10)	0.934	0.924	0.909	0.935	0.949	0.945	0.942	0.928	0.905	0.945	0.941	0.957	0.939	0.927	0.945	0.953	0.950	0.947	0.941	0.911	0.950	0.944
11)	0.982	0.952	0.969	0.946	0.950	0.934	0.965	0.947	0.972	0.945	0.972	0.982	0.959	0.971	0.955	0.955	0.943	0.969	0.948	0.978	0.958	0.982
	Region $\bar{i} = c$																					
1)	0.061	0.120	0.117	0.063	0.077	0.103	0.067	0.045	0.036	0.086	0.071	0.065	0.113	0.111	0.064	0.075	0.111	0.071	0.048	0.035	0.089	0.082
2)	0.122	0.146	0.122	0.115	0.112	0.054	0.086	0.105	0.069	0.079	0.108	0.117	0.111	0.115	0.105	0.107	0.055	0.082	0.095	0.070	0.078	0.104
3)	0.071	0.072	0.136	0.088	0.089	0.069	0.084	0.112	0.141	0.091	0.112	0.072	0.071	0.118	0.082	0.098	0.069	0.086	0.128	0.165	0.091	0.131
4)	0.047	0.204	0.036	0.139	0.036	0.225	0.036	0.064	0.022	0.028	0.023	0.058	0.179	0.057	0.129	0.049	0.187	0.054	0.070	0.032	0.038	0.032
5)	0.002	0.030	0.019	0.040	0.046	0.010	0.017	0.027	0.006	0.014	0.006	0.003	0.021	0.015	0.043	0.054	0.010	0.018	0.030	0.006	0.013	0.004
6)	0.011	0.016	0.009	0.023	0.012	0.013	0.015	0.012	0.011	0.013	0.012	0.010	0.013	0.008	0.017	0.010	0.014	0.014	0.012	0.010	0.012	0.010
7)	0.025	0.043	0.029	0.166	0.029	0.032	0.037	0.122	0.045	0.050	0.037	0.026	0.044	0.031	0.153	0.033	0.033	0.036	0.109	0.046	0.050	0.041
8)	0.135	0.181	0.170	0.206	0.099	0.099	0.176	0.193	0.178	0.209	0.214	0.149	0.183	0.171	0.207	0.108	0.097	0.181	0.185	0.158	0.187	0.179
9)	0.040	0.050	0.053	0.047	0.041	0.044	0.040	0.038	0.039	0.041	0.046	0.043	0.061	0.059	0.056	0.047	0.047	0.044	0.039	0.043	0.047	0.049
10)	0.059	0.066	0.079	0.055	0.043	0.046	0.049	0.067	0.087	0.045	0.051	0.040	0.055	0.067	0.048	0.039	0.042	0.044	0.055	0.080	0.040	0.045
11)	0.018	0.048	0.031	0.054	0.049	0.066	0.035	0.053	0.028	0.055	0.028	0.017	0.039	0.026	0.043	0.044	0.056	0.030	0.052	0.021	0.041	0.017
											Region $i = c$ (ROW)											
	Region $\bar{i} = a$ (DEU)											Region $\bar{i} = a$ (ESP)										
1)	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
3)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
4)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
5)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
8)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9)	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
11)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Region $\bar{i} = b$																					
1)	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
2)	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
3)	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
4)	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
5)	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
6)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
7)	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
8)	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
9)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
10)	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
11)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
	Region $\bar{i} = c$																					
1)	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
2)	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971
3)	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956	0.956
4)	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971
5)	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.973	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996
6)	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998
7)	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987
8)	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.962	0.960	0.960	0.960	0.960	0.960	0.960	0.960	0.960	0.960	0.960	0.960
9)	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.981	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.980
10)	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.976	0.975	0.975	0.975	0.975	0.975	0.975	0.975	0.975	0.975	0.975	0.975
11)	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992

Notes: This table reports parameter values for the sector-specific preference biases $hb_{H,s,i,\bar{i}}$, of region i towards goods produced in region $\bar{i}$ for the model calibration with Germany or Spain as individual region a. These were computed based on the World Input-Output Database for the year 2014. Parameters for region $i = c$ were used to close the model. Hence, home biases of this region might slightly differ across both model calibrations.

Table A.6: Calibration of environmental parameters

Variable/Parameter	Symbol	Value	
Pollution decay	$1-\rho^{EM}$	0.9979	
Abatement cost parameter (potent)	$\phi_{2,i}$	2.8	
Abatement cost parameter (proportional)	$\phi_{1,a}$	$\phi_{1,b}$	$\phi_{1,c}$
	0.036	0.036	0.050
Damage parameter (constant)	$\gamma_{0,DEU}$	$\gamma_{0,b}$	$\gamma_{0,c}$
	-0.0052	-0.0052	-0.0068
Damage parameter (proportional)	$\gamma_{1,DEU}$	$\gamma_{1,b}$	$\gamma_{1,c}$
	-2.8047e-04	-2.8047e-0	-3.1835e-04
Damage parameter (quadratic)	$\gamma_{2,DEU}$	$\gamma_{2,b}$	$\gamma_{2,c}$
	9.0645e-06	9.0645e-06	1.071e-05
Damage parameter (constant)	$\gamma_{0,ESP}$	$\gamma_{0,b}$	$\gamma_{0,c}$
	-0.0052	-0.0052	-0.0068
Damage parameter (proportional)	$\gamma_{1,ESP}$	$\gamma_{1,b}$	$\gamma_{1,c}$
	-2.0948e-04	-2.0948e-04	-2.3266e-04
Damage parameter (quadratic)	$\gamma_{2,ESP}$	$\gamma_{2,b}$	$\gamma_{2,c}$
	4.8240e-06	4.8240e-06	5.7192e-06

Notes: This table reports the calibrated environmental parameters of the model, described in the main text. Carbon intensities were computed by the authors based on the World Input Output Database and environmental accounts and refer to 2014.

Appendix B: Additional results

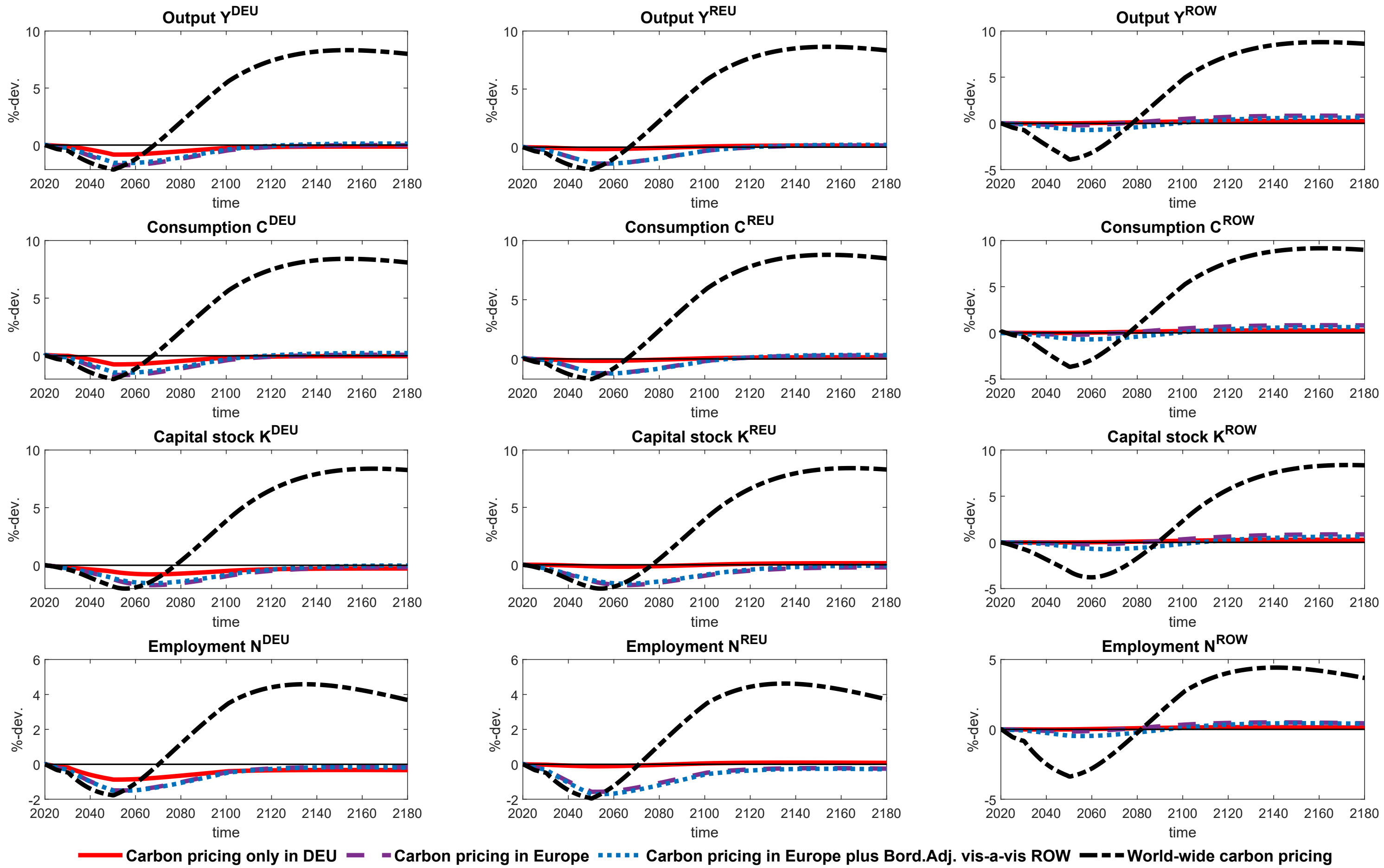
In this appendix, we show

(i.) more detailed results on all scenarios (including world-wide carbon pricing) for both model calibrations in Figures A.1-A.8,

(ii.) the results of all scenarios when neglecting economic emissions damage in Figures A.9-A.14,

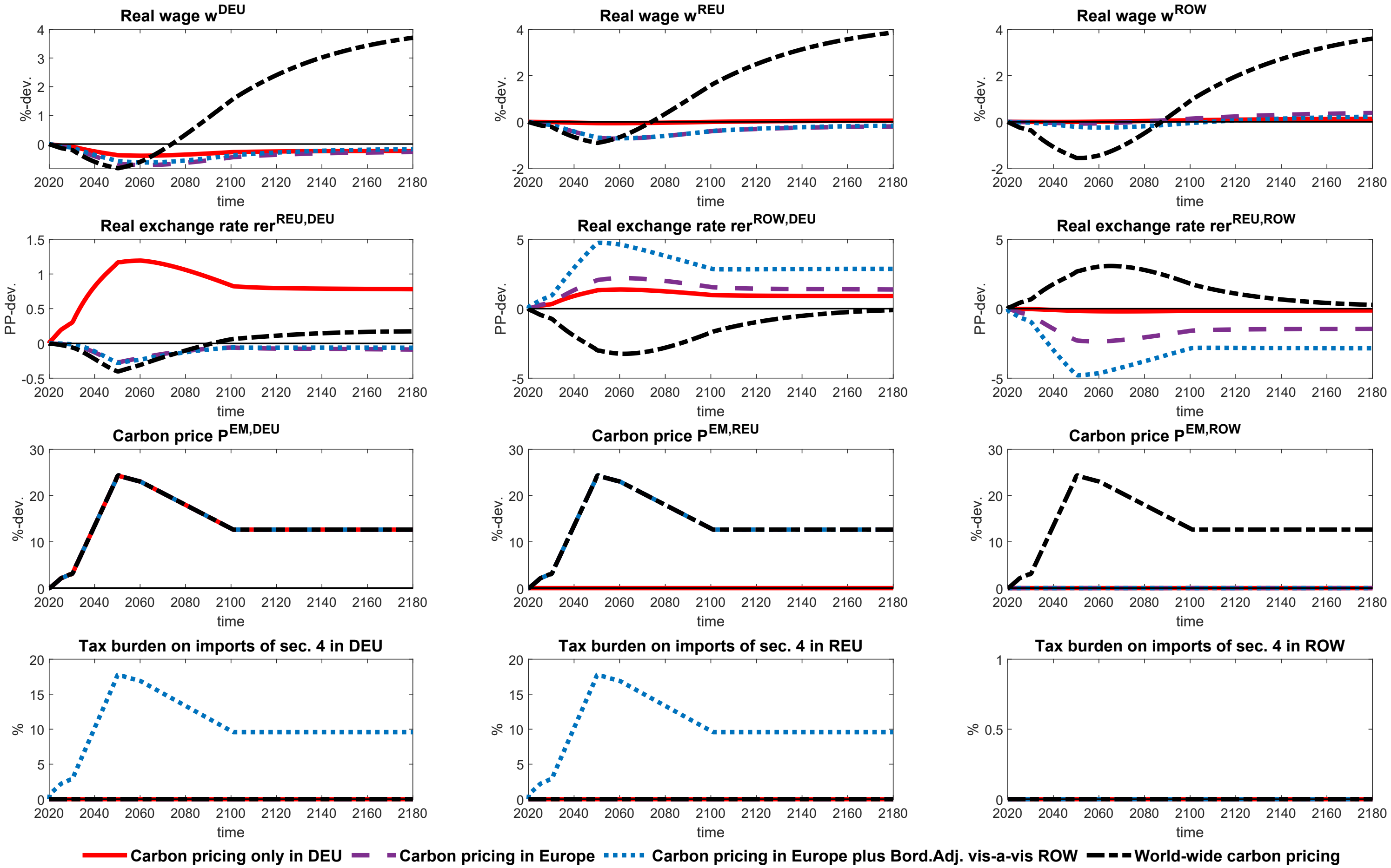
(iii.) the results of all scenarios when only EU ETS are subject to the carbon price A.15-A.20.

Figure A.1: Effects of carbon pricing on key macroeconomic variables in Germany, rest of Europe and the rest of the world (all scenarios)



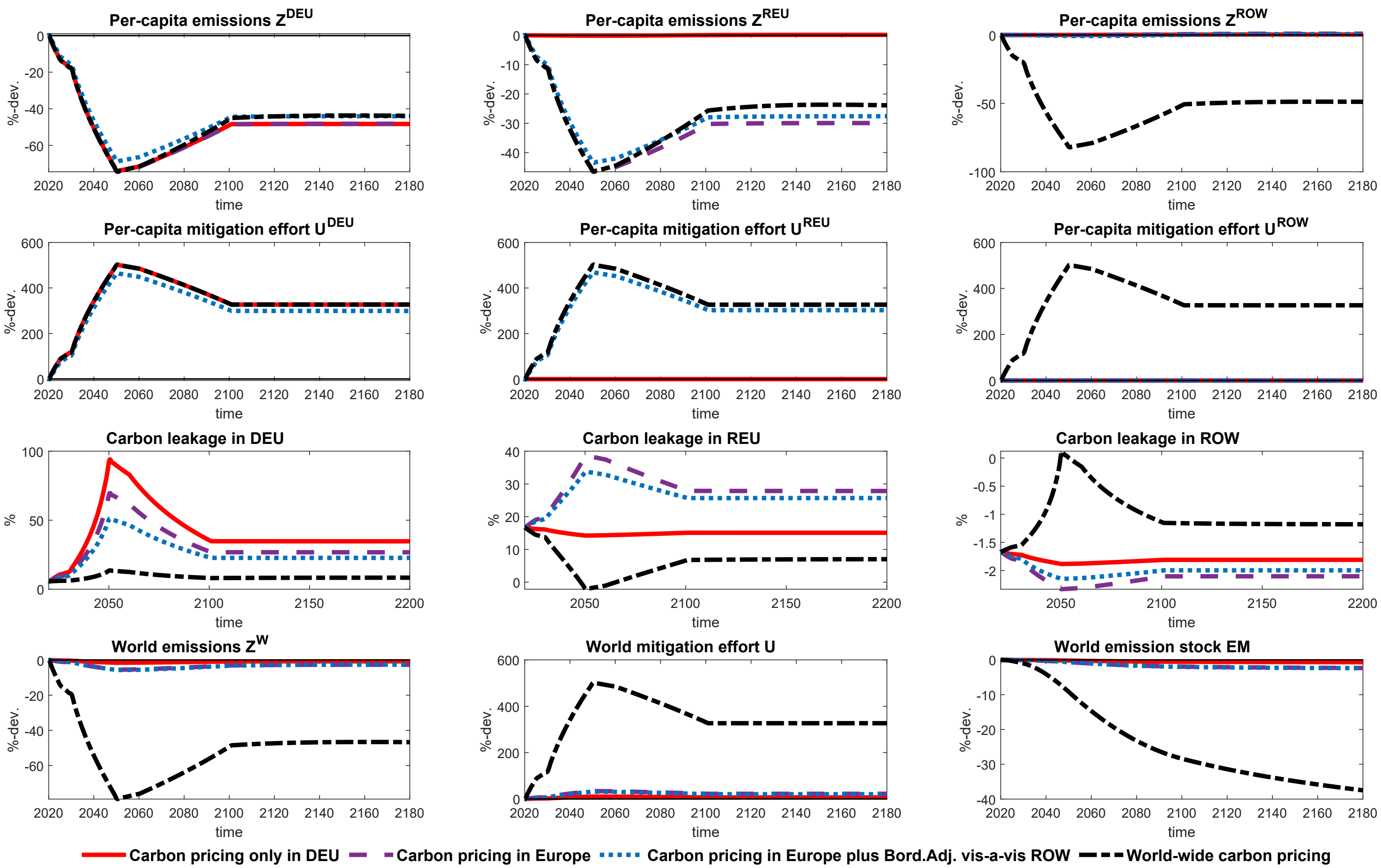
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Germany (*a*) only. Carbon pricing in whole Europe (*a* and *b*) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions *a*, *b* and *c* by the solid black line.

Figure A.2: Effects of carbon pricing on selected factor/relative prices in Germany, rest of Europe and the rest of the world (all scenarios)



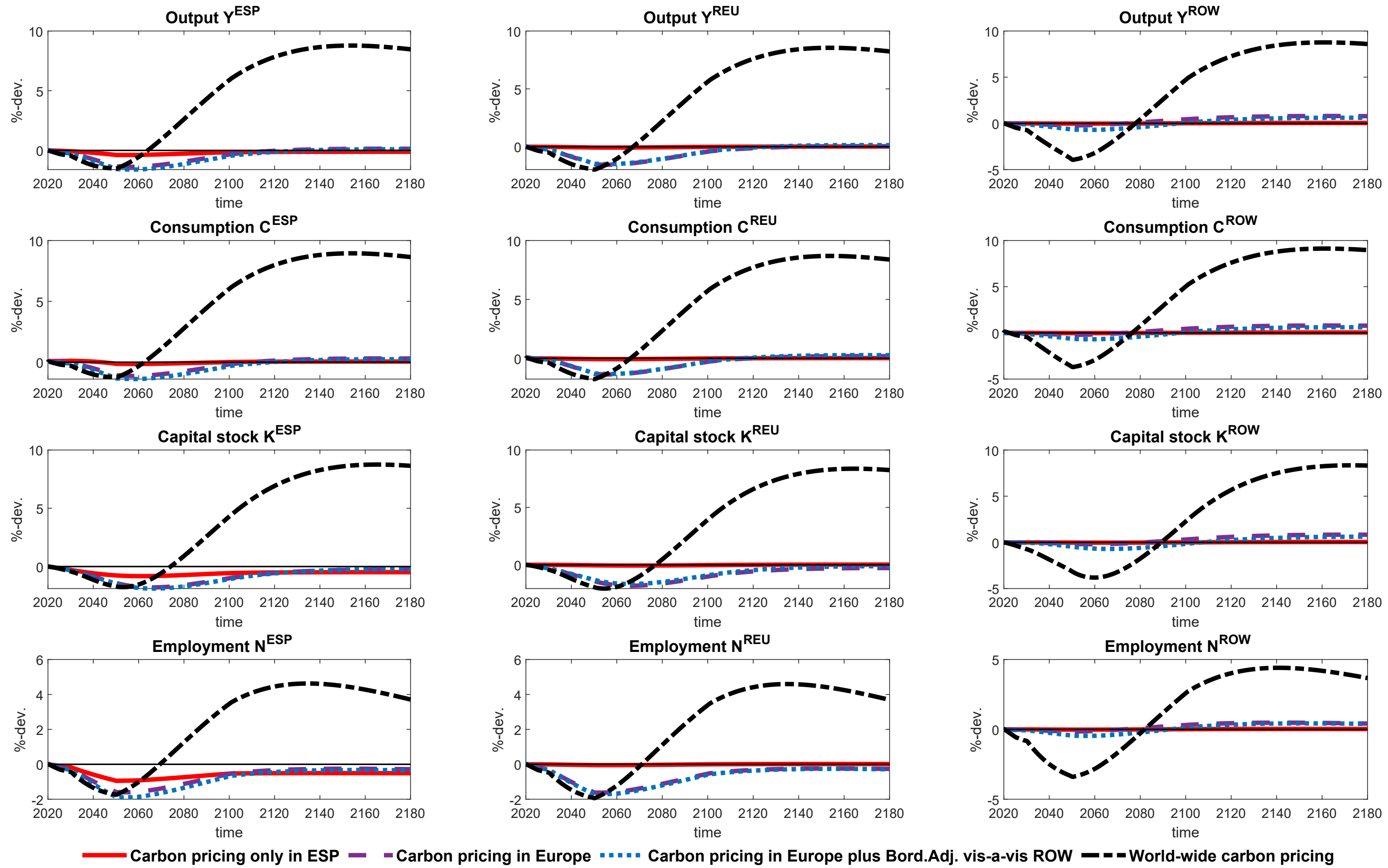
Notes: Figure plots (projected) implications of carbon pricing for selected factor/relative prices in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Germany (*a*) only. Carbon pricing in whole Europe (*a* and *b*) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions *a*, *b* and *c* by the solid black line.

Figure A.3: Effects of carbon pricing on selected environmental variables in Germany, rest of Europe and the rest of the world (all scenarios)



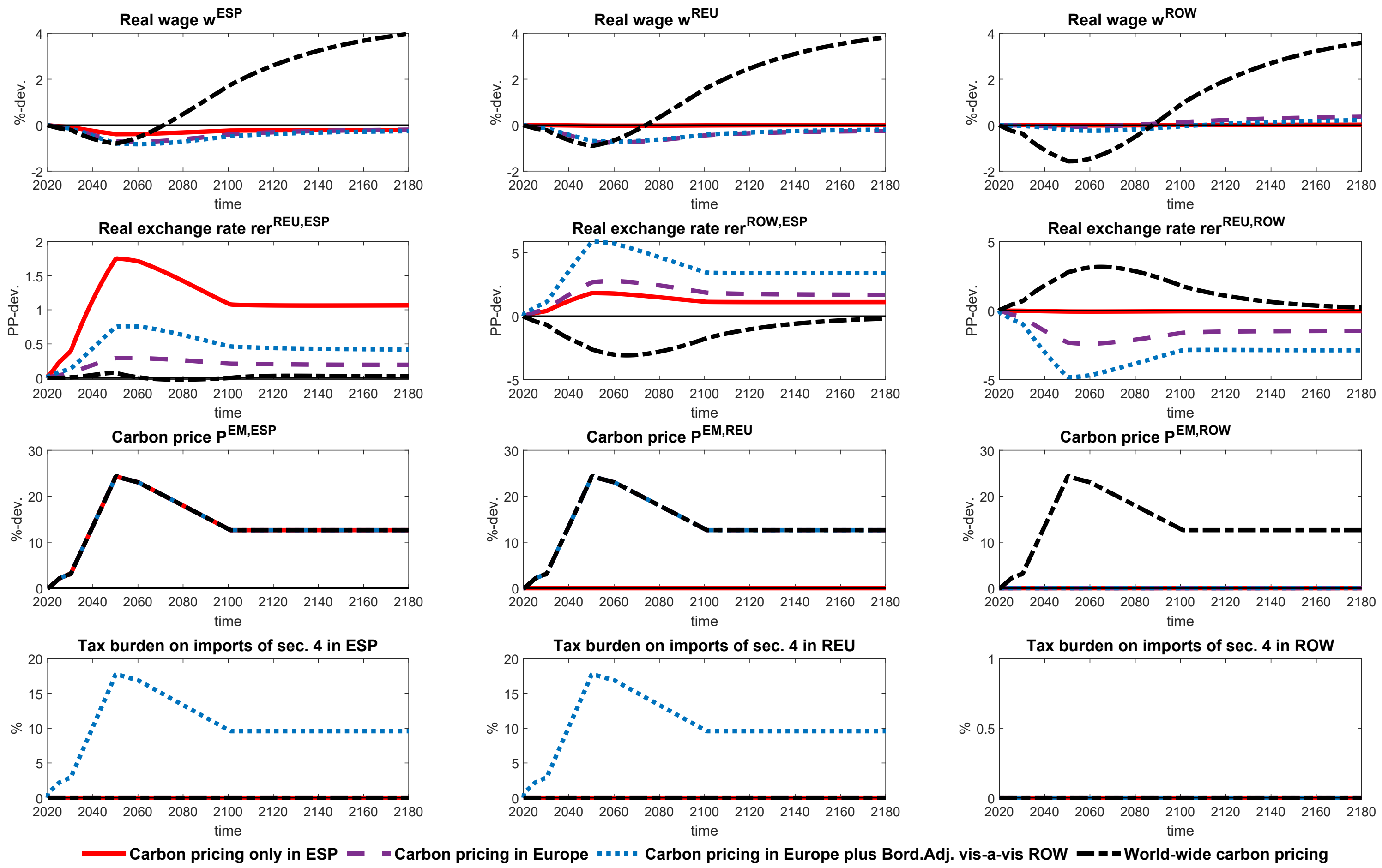
Notes: Figure plots (projected) implications of carbon pricing for selected environmental in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Germany (a) only. Carbon pricing in whole Europe (a and b) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions a, b and c by the solid black line.

Figure A.4: Effects of carbon pricing on key macroeconomic variables in Spain, rest of Europe and the rest of the world (all scenarios)



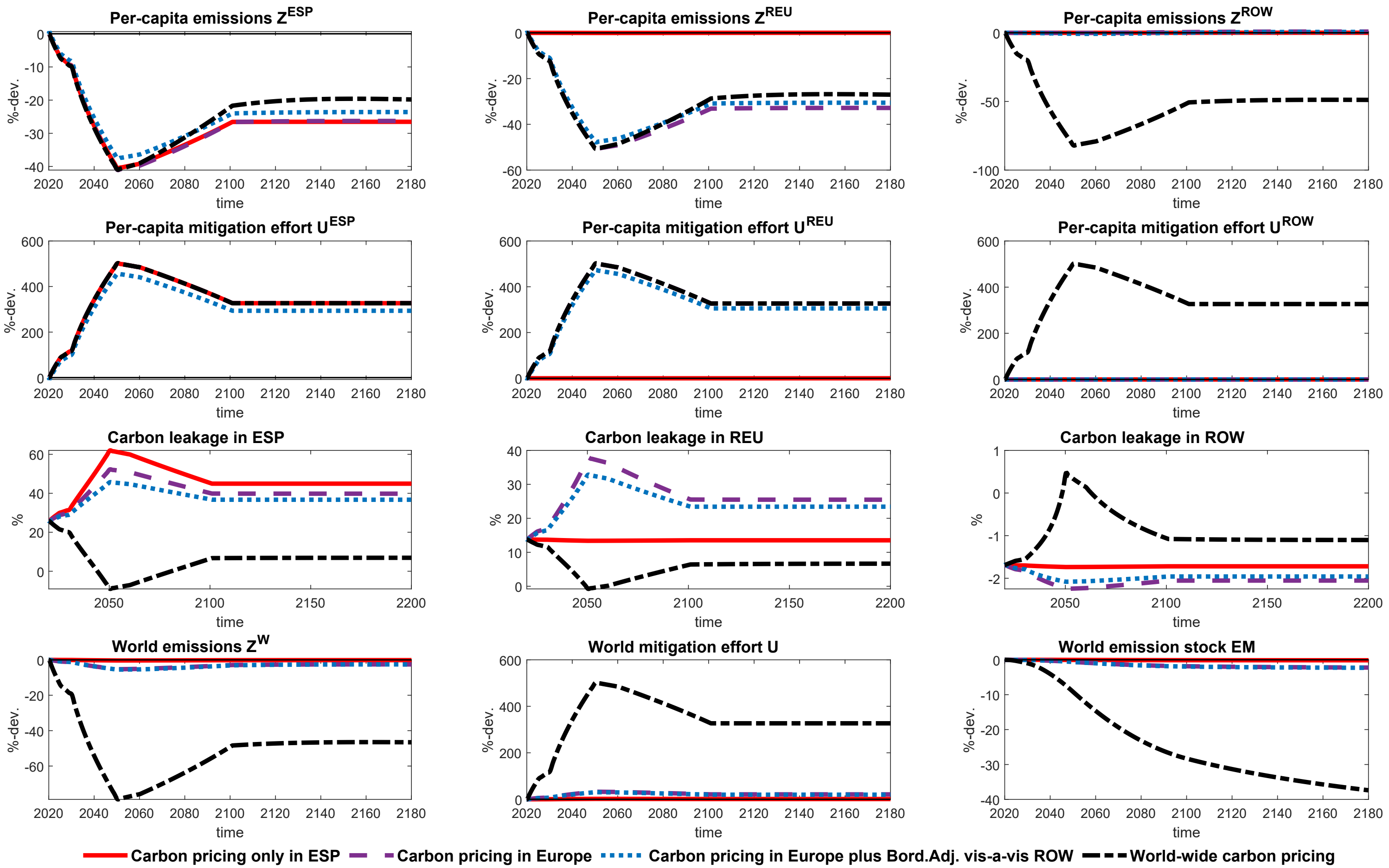
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Spain (*a*) only. Carbon pricing in whole Europe (*a* and *b*) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions *a*, *b* and *c* by the solid black line.

Figure A.5: Effects of carbon pricing on selected factor/relative prices in Spain, rest of Europe and the rest of the world (all scenarios)



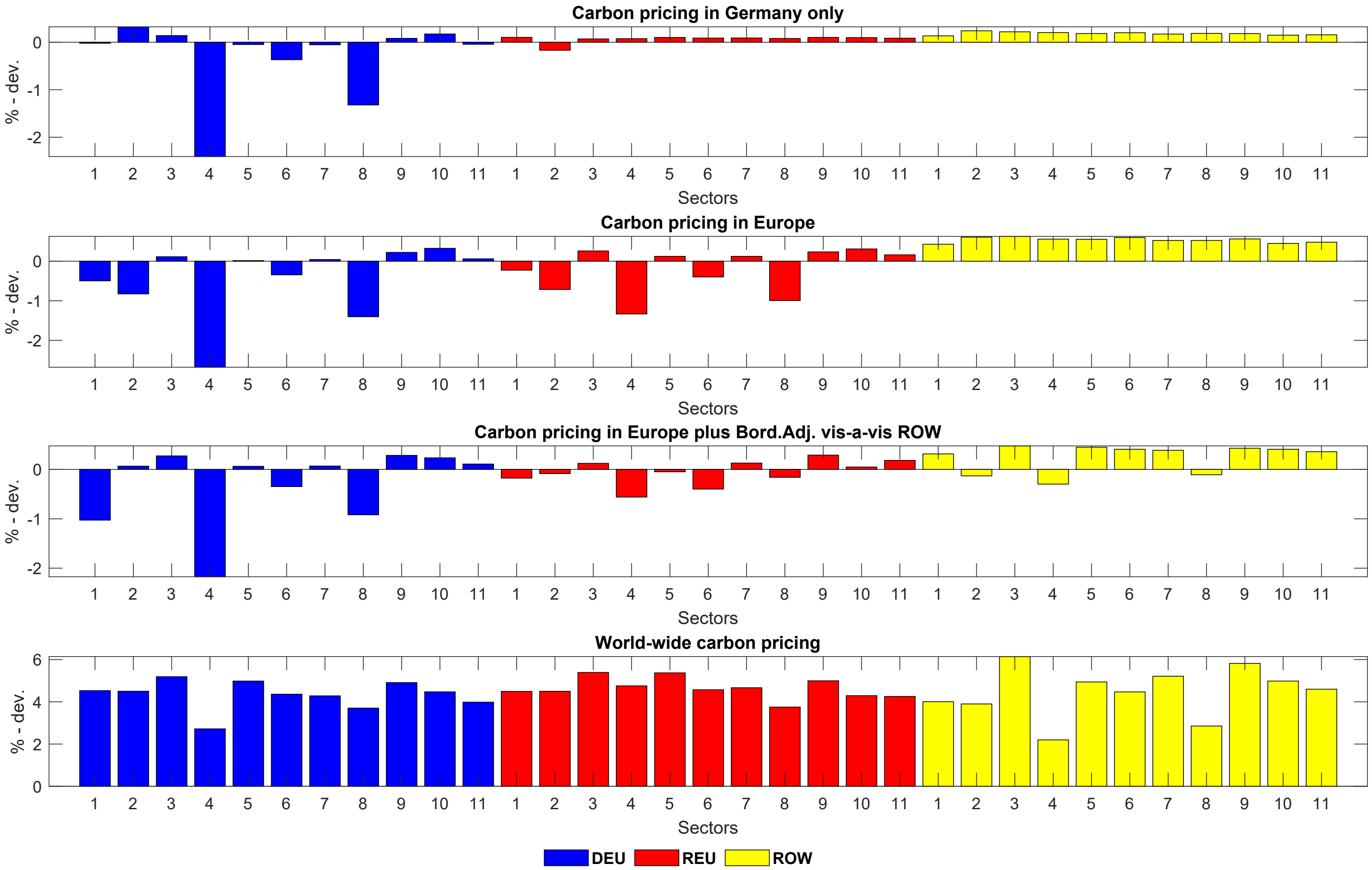
Notes: Figure plots (projected) implications of carbon pricing for selected factor/relative prices in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Spain (a) only. Carbon pricing in whole Europe (a and b) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions a, b and c by the solid black line.

Figure A.6: Effects of carbon pricing on selected environmental variables in Spain, rest of Europe and the rest of the world (all scenarios)



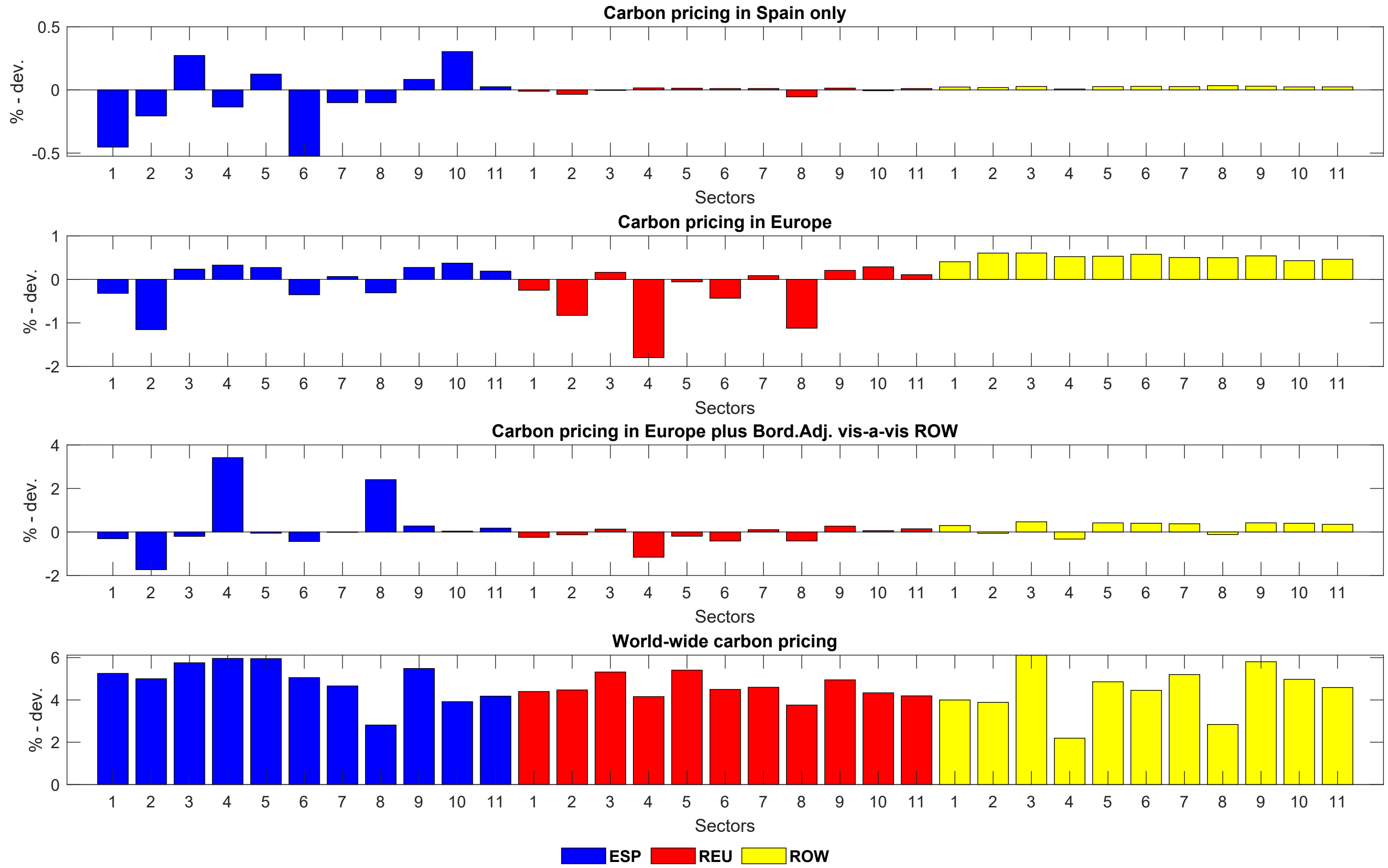
Notes: Figure plots (projected) implications of carbon pricing for selected environmental in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region Spain (a) only. Carbon pricing in whole Europe (a and b) is depicted by the purple dotted line, a European climate club including border adjustment by the dashed blue line, and carbon pricing in all regions a, b and c by the solid black line.

Figure A.7: Long-run changes in sectoral value added implied by carbon pricing (Germany, rest of Europe, rest of the world)



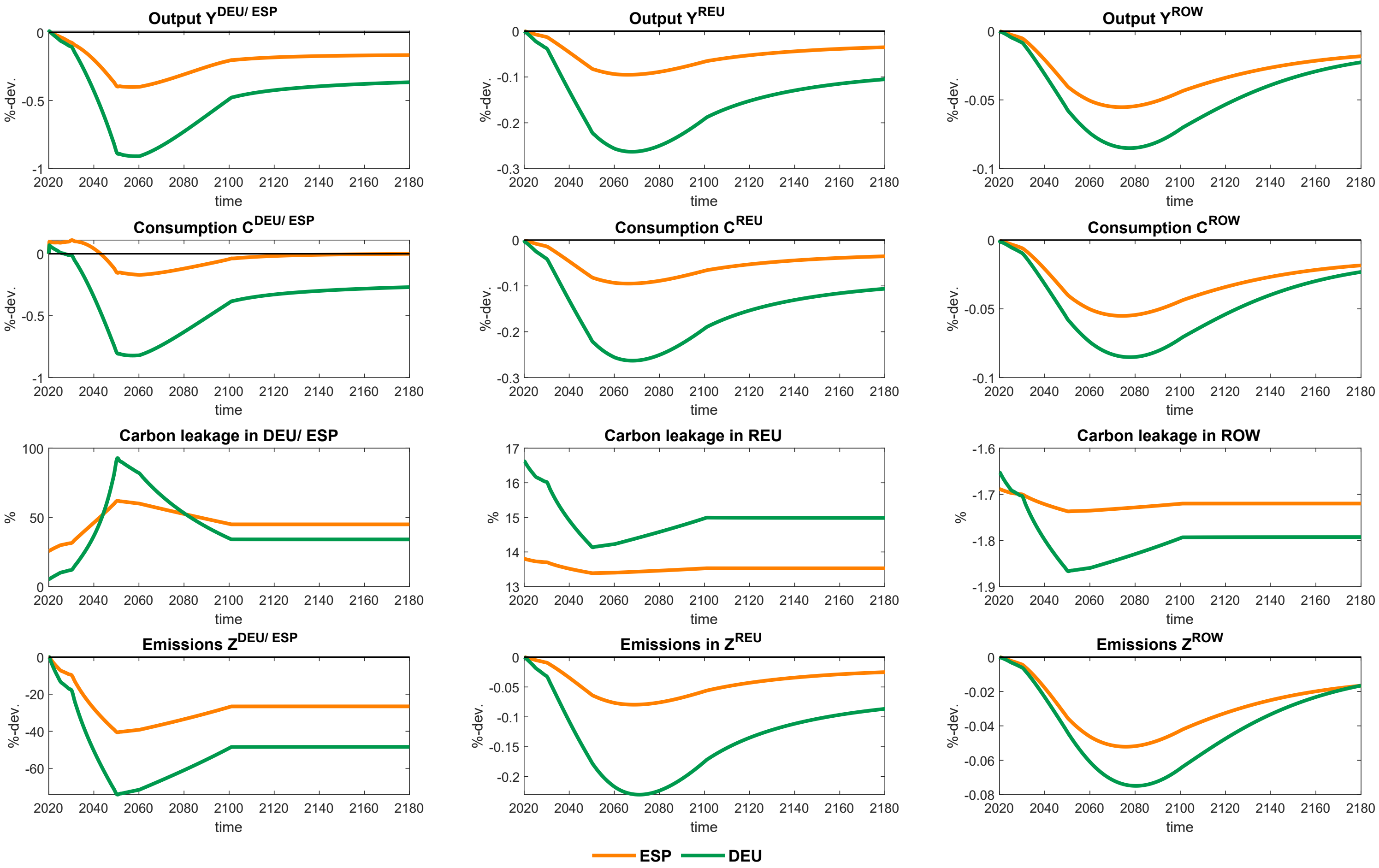
Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for Germany (blue bars), rest of Europe (red bars) and the rest of the world (yellow bars). Scenarios are according to headline.

Figure A.8: Long-run changes in sectoral value added implied by carbon pricing (Spain, rest of Europe, rest of the world)



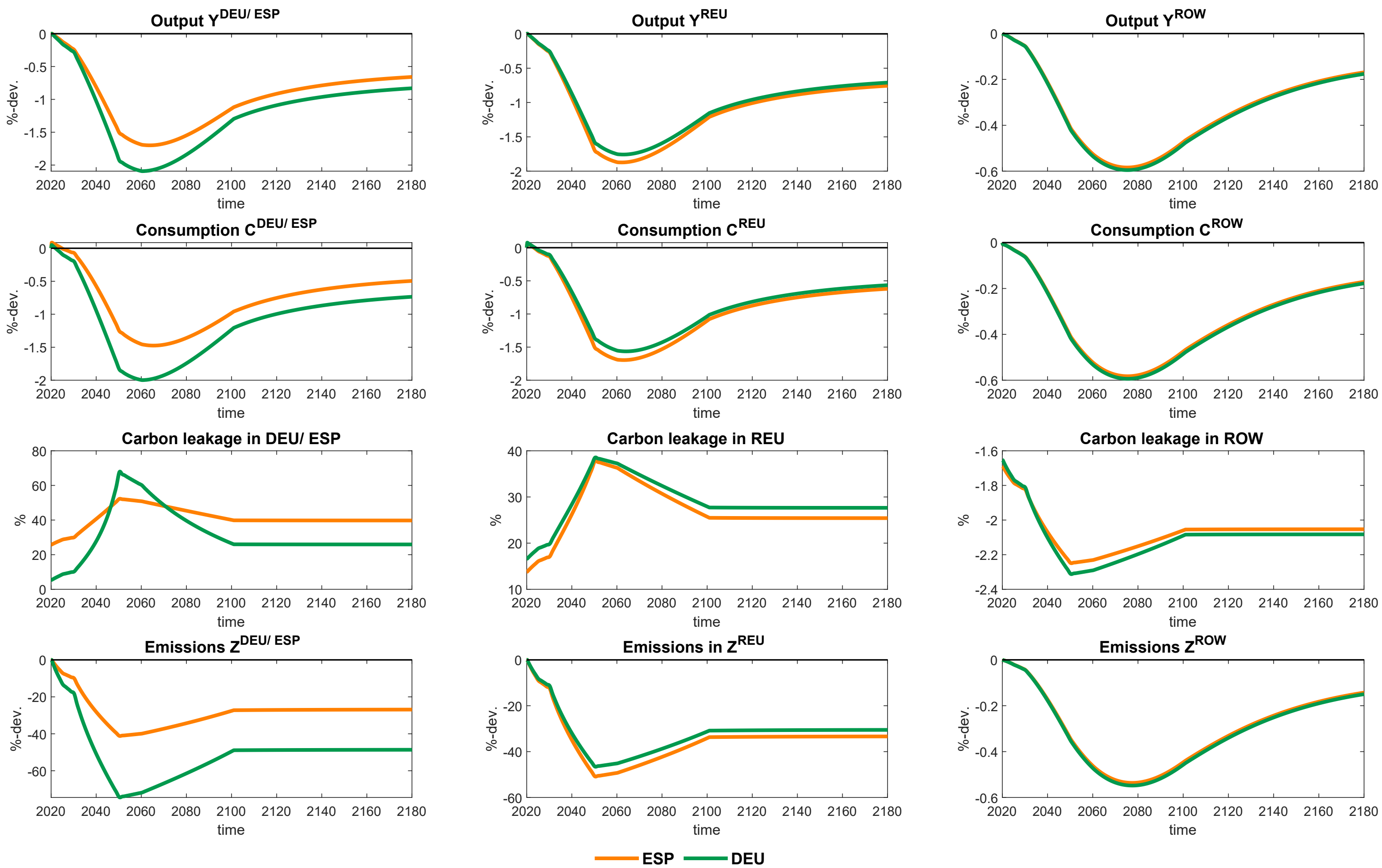
Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for Spain (blue bars), rest of Europe (red bars) and the rest of the world (yellow bars). Scenarios are according to headline.

Figure A.9: Carbon pricing in *a* only (Germany vs. Spain) without damage



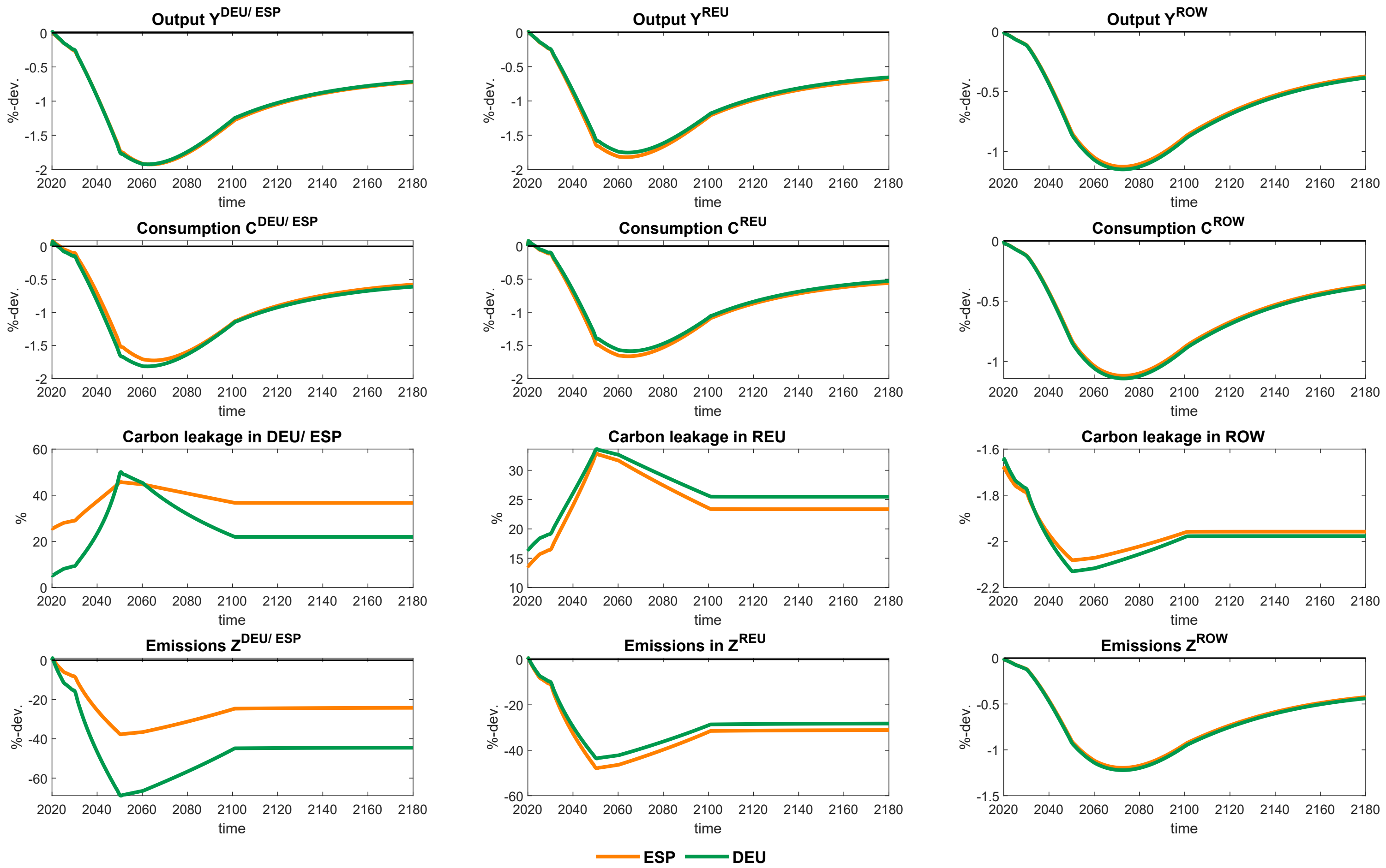
Notes: Figure plots (projected) implications of carbon pricing in *a* only for selected variables in the three regions without damage from emissions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.10: Carbon pricing in a and b (Germany vs. Spain) without damage



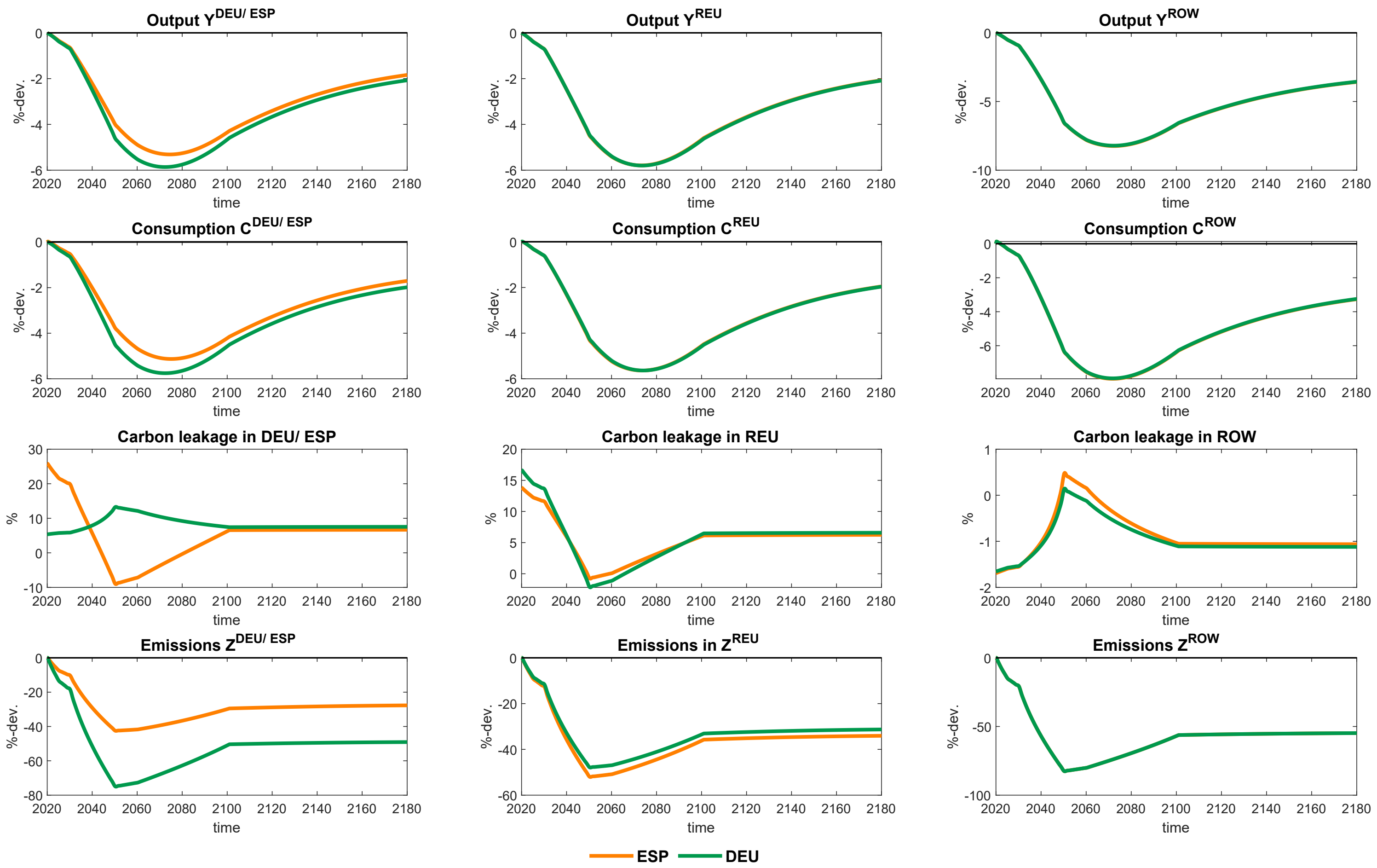
Notes: Figure plots (projected) implications of carbon pricing in a and b for selected variables in the three regions without damage from emissions. The green lines refer to the calibration with Germany being region a. Orange lines indicate the calibration for Spain.

Figure A.11: Carbon pricing in a and b plus border adjustment (Germany vs. Spain) without damage



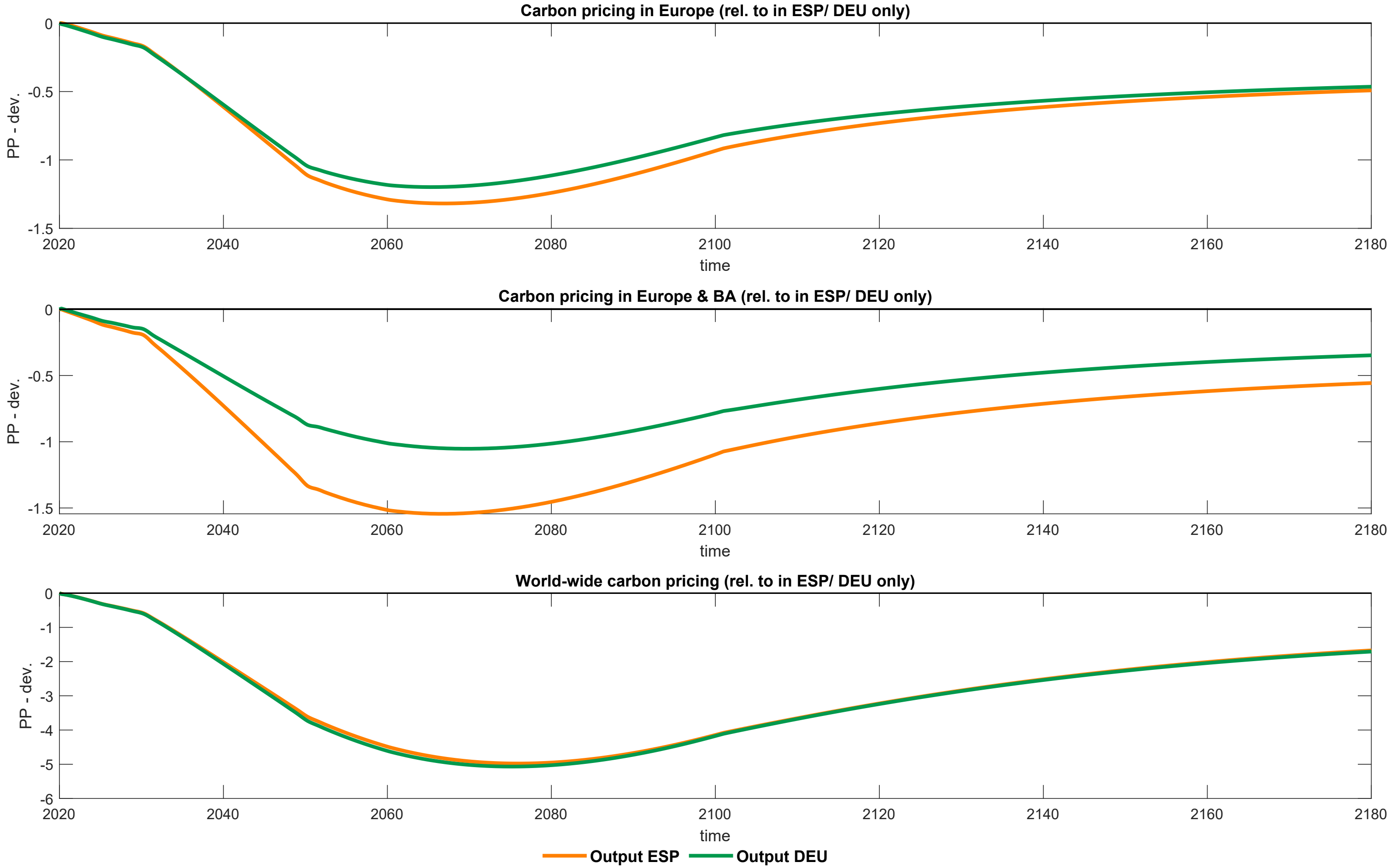
Notes: Figure plots (projected) implications of carbon pricing in a and b plus border adjustment vis-a-vis c for selected variables in the three regions without damage from emissions. The green lines refer to the calibration with Germany being region a. Orange lines indicate the calibration for Spain.

Figure A.12: World-wide carbon pricing (Germany vs. Spain) without damage



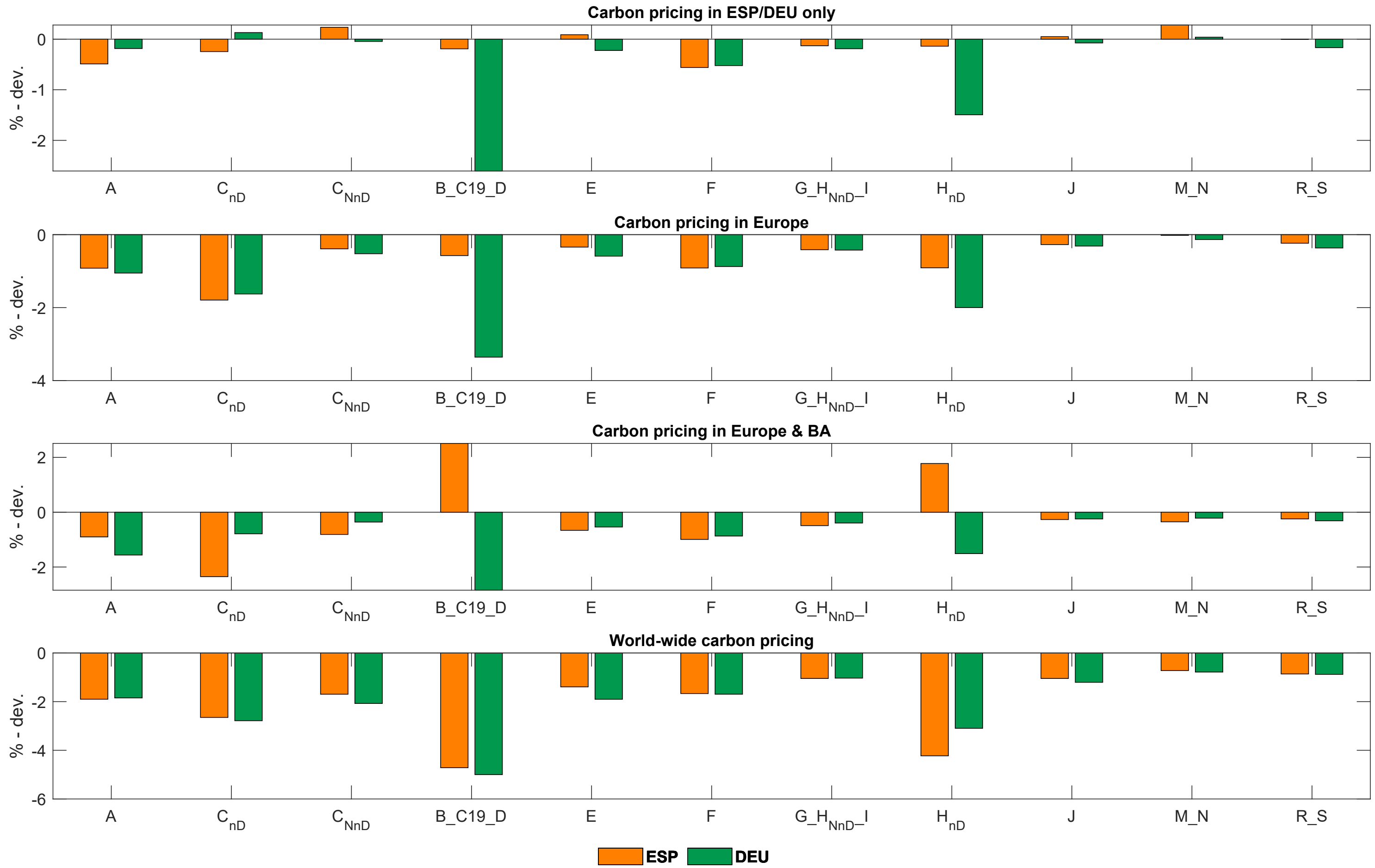
Notes: Figure plots (projected) implications of world-wide carbon pricing for selected variables in the three regions without damage from emissions. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.13: Carbon pricing scenarios relative to first scenario (Germany vs. Spain) without damage



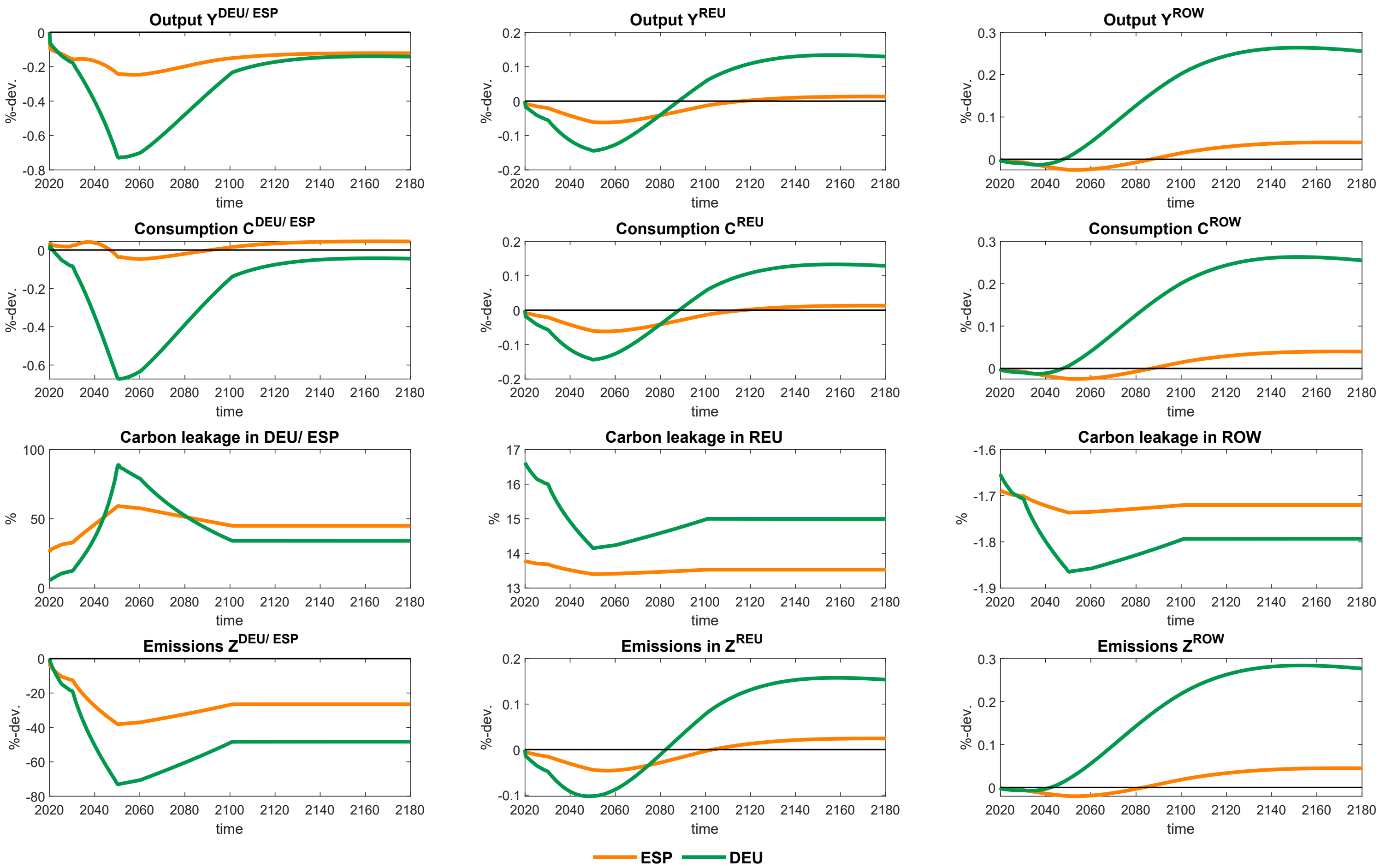
Notes: Figure plots (projected) implications of different carbon pricing scenarios relative to the one where only region a introduces the price for selected variables in the three regions without damage from emissions. The green lines refer to the calibration with Germany being region a. Orange lines indicate the calibration for Spain.

Figure A.14: Long-run changes in sectoral value added implied by carbon pricing (Germany vs. Spain) without damage



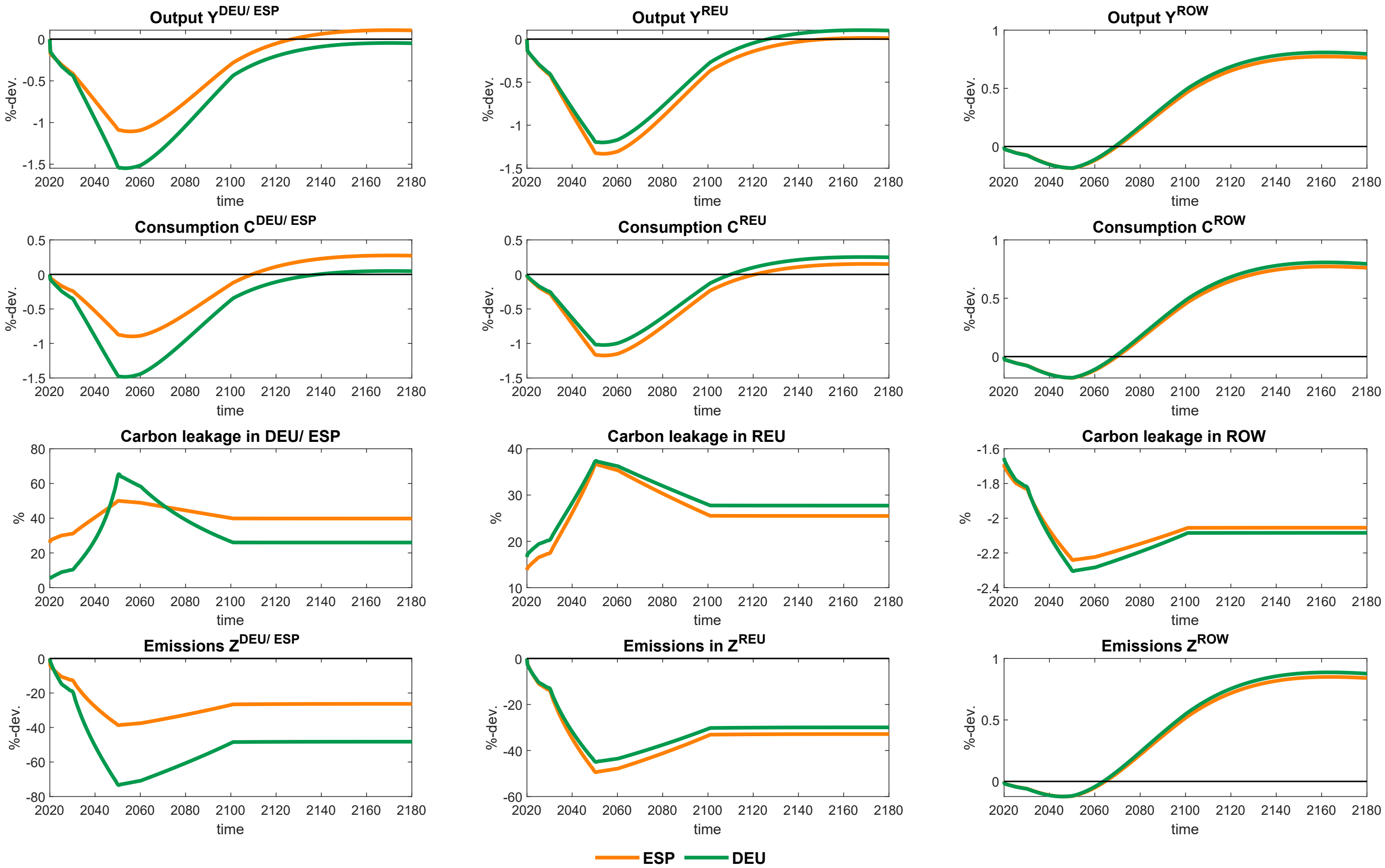
Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for Germany (green bars) and Spain (orange bars) without damage from emissions. Scenarios are according to headline.

Figure A.15: ETS carbon pricing in *a* only (Germany vs. Spain)



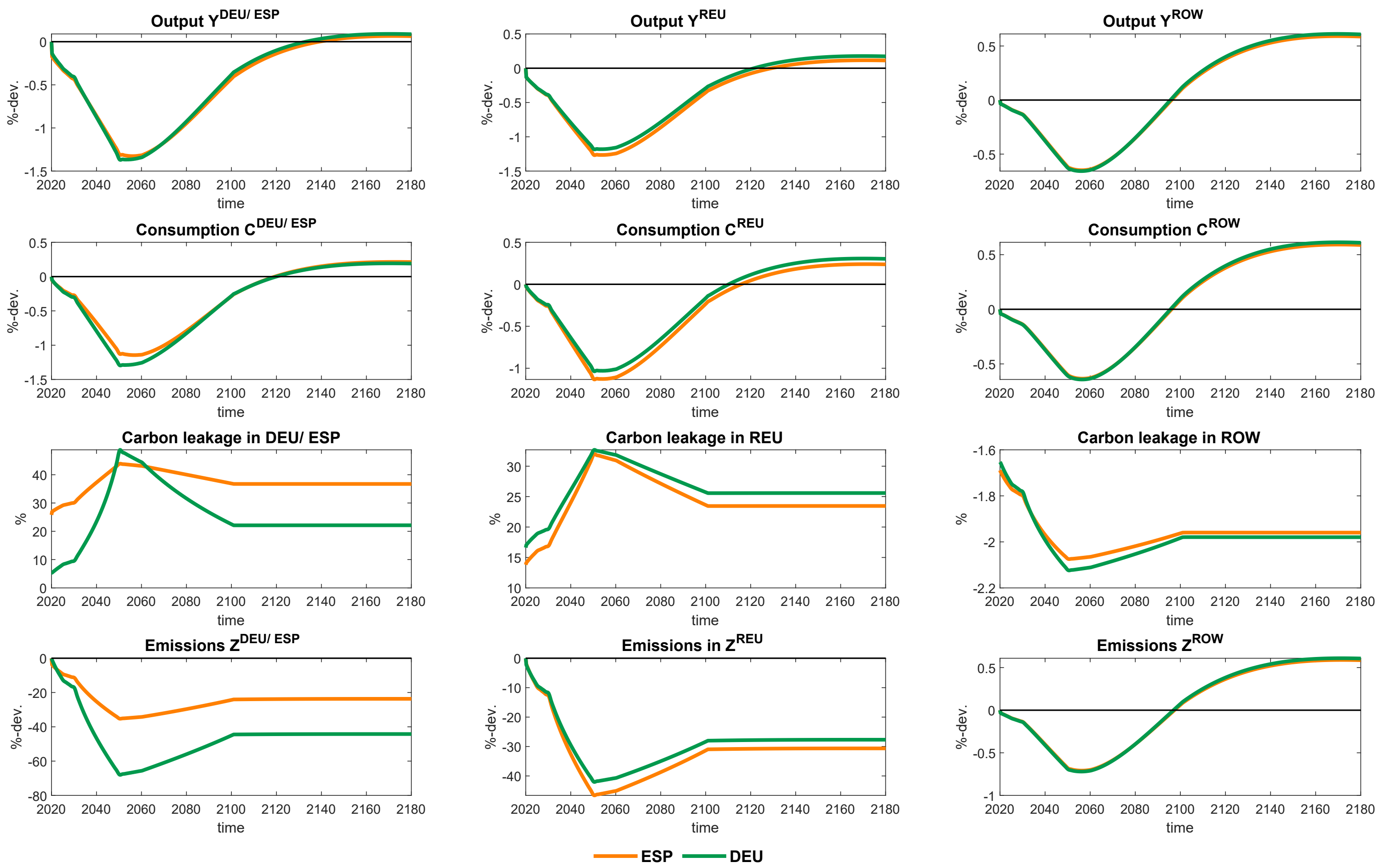
Notes: Figure plots (projected) implications of carbon pricing in *a* only for selected variables in the three regions, when only ETS sectors are priced.. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.16: ETS carbon pricing in *a* and *b* (Germany vs. Spain)



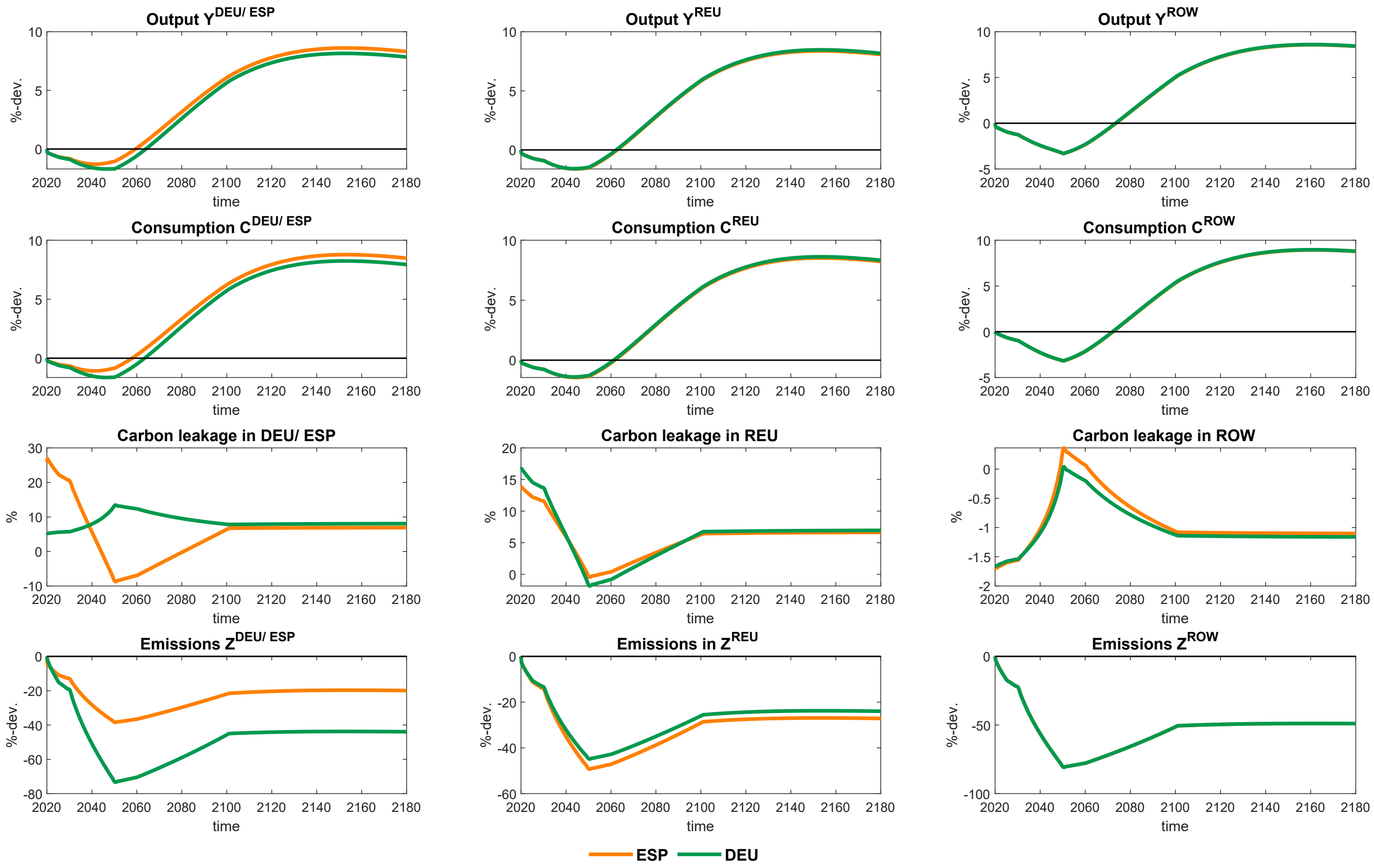
Notes: Figure plots (projected) implications of carbon pricing in *a* and *b* for selected variables in the three regions, when only ETS sectors are priced. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.17: ETS carbon pricing in *a* and *b* plus border adjustment (Germany vs. Spain)



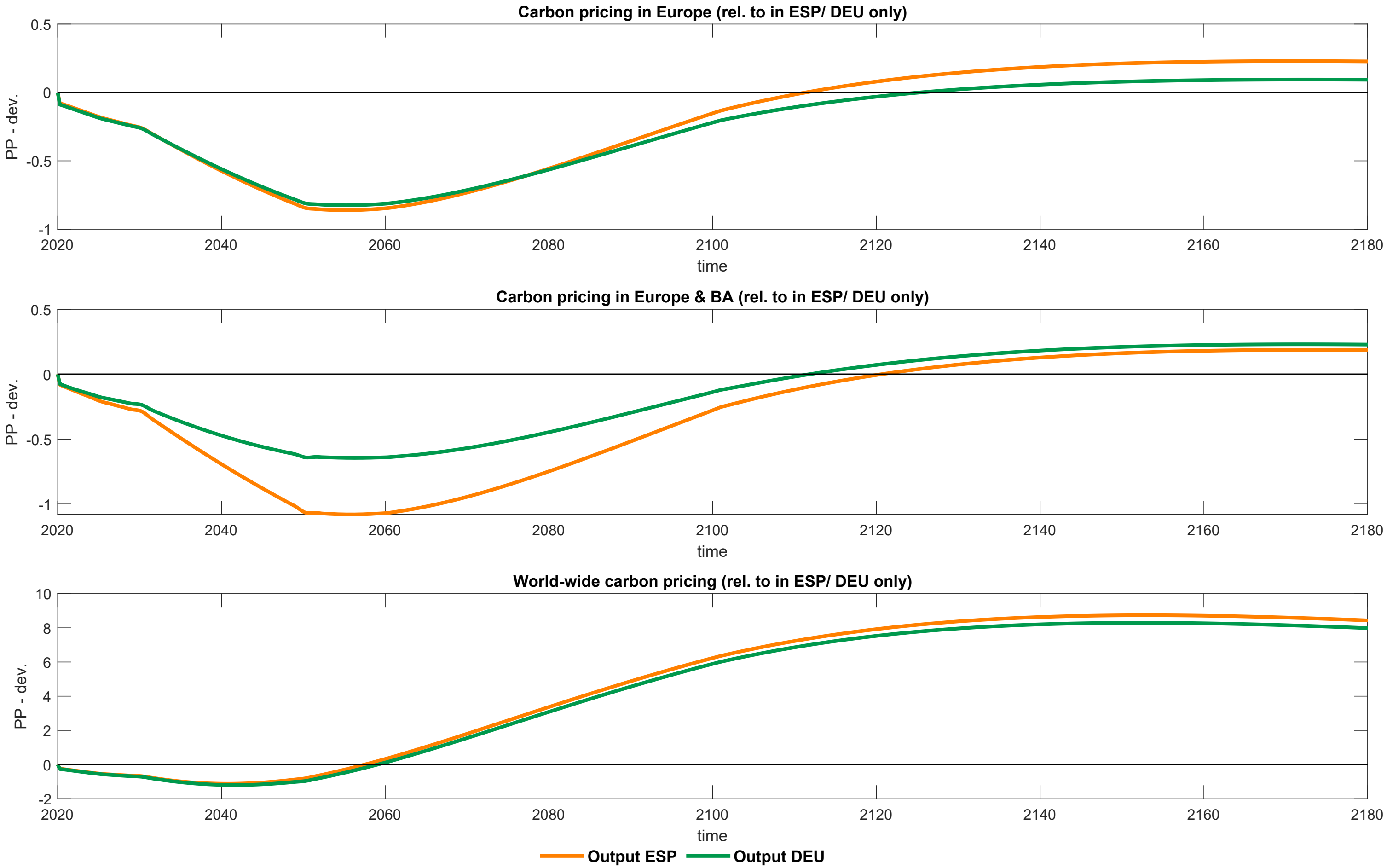
Notes: Figure plots (projected) implications of carbon pricing in *a* and *b* plus border adjustment vis-a-vis *c* for selected variables in the three regions, when only ETS sectors are priced. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.18: World-wide ETS carbon pricing (Germany vs. Spain)



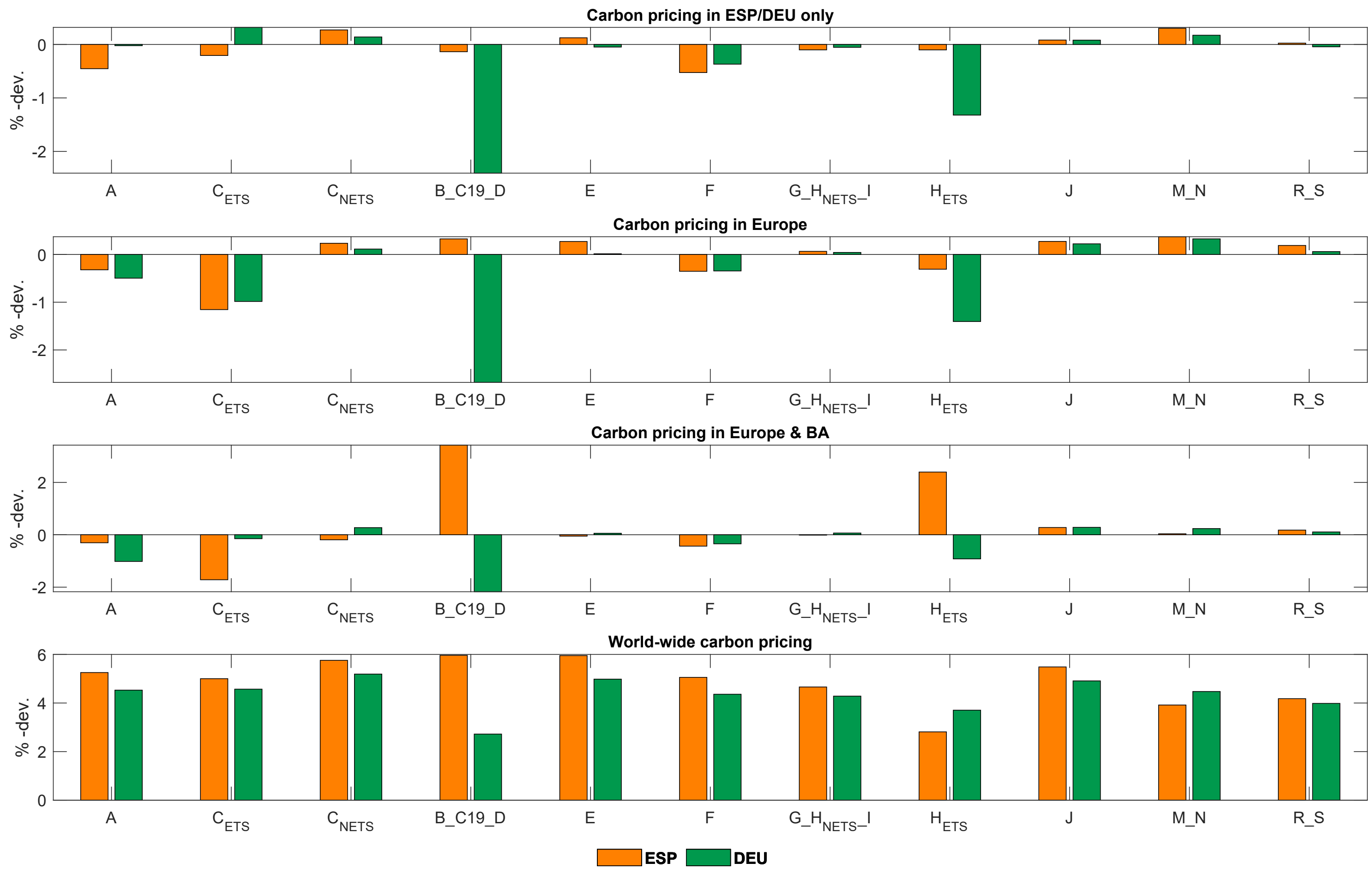
Notes: Figure plots (projected) implications of world-wide carbon pricing for selected variables in the three regions, when only ETS sectors are priced. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.19: ETS carbon pricing scenarios relative to first ETS scenario (Germany vs. Spain)



Notes: Figure plots (projected) implications of different carbon pricing scenarios relative to the one where only region *a* introduces the price for selected variables in the three regions, when only ETS sectors are priced. The green lines refer to the calibration with Germany being region *a*. Orange lines indicate the calibration for Spain.

Figure A.20: Long-run changes in sectoral value added implied by ETS carbon pricing (Germany vs. Spain)



Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for Germany (green bars) and Spain (orange bars), when only ETS sectors are priced. Scenarios are according to headline.

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