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Abstract

In this paper, we compare the economic and welfare implications of two carbon pricing policies, namely the European Cap and Trade (CaT) regime and the Chinese Tradeable Performance Standard (TPS). The former sets an economy-wide emissions target and forces firms to purchase sufficient certificates. The latter sets an emissions intensity and requires firms with a higher intensity to either abate or buy emissions allowances from firms with lower-than-target intensities. It can be shown that TPS is equivalent to CaT when carbon pricing revenues are redistributed to firms according to output. In a dynamic multi-sector general equilibrium TANK model, we show that TPS outperforms a CaT regime that redistributes carbon revenues to households in a lump-sum manner, both, in terms of output gains and welfare due to lower costs on the production side. However, CaT with labor tax reduction increases welfare most because it alleviates distortions on the production side and improves the income situation of all households.

Keywords: Carbon Pricing, Cap and Trade, Tradable Performance Standard, Dynamic General Equilibrium Model, Sectoral Heterogeneity, Input-Output Matrix

JEL classification: E32, E62, H23, H32, Q58

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1 Introduction

Sixteen years after the launch of the European Union Emissions Trading System (EU-ETS) on greenhouse gas emissions, China has started its own system in 2021. Though similar in the goal of reducing greenhouse gas emissions through pricing, the two systems differ regarding their policy variables as well as in the distribution of revenues. The EU-ETS is a Cap and Trade system (CaT), which imposes a cap on total emissions, and allows for trade in the corresponding emissions allowances. As emissions allowances are sold to firms via auctions, they generate government revenue, which e.g. can be redistributed to households. The Chinese system, on the other hand, determines a permitted emissions intensity of the economy and distributes emissions allowances accordingly. This so-called Tradeable Performance Standard (TPS) targets the average emissions intensities of the covered sectors. Each covered firm receives emission allowances free of charge in the amount of its production multiplied by the targeted average emissions intensity. Similar to the EU-ETS, firms can trade emissions allowances. Firms that produce with a lower than targeted emissions intensity will sell allowances to firms which produce with a higher than targeted emissions intensity. In contrast to CaT, TPS does not generate government revenue.

The Chinese TPS requires a detailed knowledge about production and demand functions in order to reach a desired emissions reduction. However, we abstract from these more practical issues. Instead, we focus on the impact of the two systems on the macroeconomy and analyse where differences stem from. Interestingly, we find that TPS performs better in terms of output, consumption and employment. However, we can show that this results from the use of government revenues under CaT. If government subsidizes output in CaT similar to TPS, differences disappear. As this finding is crucial for our further analysis, let us have a closer look at the mechanisms.

Imagine an economy with two production sectors A and B, each of which depicted by a representative firm (A and B in the following). The firms emit carbon dioxide as a by-product of output, the resulting emissions intensities are sector-specific. Firm A's emissions intensity is lower than firm B's. Output in each sector is given by matching demand and supply. For the sake of simplicity, we assume that both firms have identical cost functions and face equal demand. Profit maximization yields that output prices equal marginal production costs. Therefore, both firms produce equal output as long as carbon emissions are not priced.

The government now introduces a CaT system: It sets an emissions target and firms must buy emissions allowances in a common auction in order to emit legally. The volume of emissions allowances corresponds to the emissions target. The fewer emissions are allowed the higher the resulting carbon price. Now, marginal production costs rise by the carbon price times the firm-specific emissions intensity. Given unchanged demand curves, each firm will lower production. As firm B has a higher emissions intensity, it reduces output more.

This allocation should not change if firms receive emissions allowances for free. The reason is that the carbon price and, hence, marginal production costs are unaffected. Due to the limited volume of allowances and the possibility to sell them on the secondary market, the opportunity cost of allowances remains the same. The free provision of emissions allowances alone does thus not change the allocation.

However, another feature of the TPS changes the allocation: The provisioning of allowances depends on the average emissions intensity determined by the government. Each firm receives emissions allowances proportionate to its production, determined by the targeted average emissions intensity. This lowers marginal production costs compared to CaT. Assume a targeted average emissions intensity that lies in-between the emissions intensities of firms A and B such that total emissions are the same as under CaT. Firm A then receives more allowances than it needs. It can sell these to firm B, which receives fewer allowances. Due to lower marginal production costs, both firms have an incentive to increase production relative to the CaT regime. Hence, in order to achieve the same emissions reduction, a higher carbon price must result under TPS. This corresponds to a lower (targeted) emissions intensity under TPS than CaT.

Finally yet importantly, assume that firms can lower their current emissions intensity by costly abatement. Marginal abatement costs are equal for both firms and increase with the level of abatement. Firms will therefore put effort in abatement as long as the marginal return is positive, i.e. marginal abatement costs will equal the carbon price. Since the carbon price is higher under TPS, firms invest more in abatement than under CaT. The higher investment in abatement in turn yields a higher additional production than under CaT.

Now, assume that the government uses the CaT proceeds to subsidize firms A and B proportionately to their output. Essentially, this is a combination of an output subsidy and an input carbon tax. In that case, the allocation changes analogously to TPS. The output subsidy has the same effect on marginal production costs and therefore incentivizes the identical production increase. To reach the same emissions reduction as before, adding an output subsidy also yields a higher carbon price under CaT. These outlined considerations suggest that TPS is equivalent to a CaT that redistributes revenues to firms according to output.

Our analysis shows that this holds also true in a more elaborated general equilibrium modelling framework.

We use a dynamic multi-sector general equilibrium TANK model with interlinked production sectors along the lines of Hinterlang, Martin, Röhe, Stähler, and Strobel (2022).[1] Our model is calibrated to the EU-27 plus UK (EU28) and, alternatively, to China using the latest version of the World Input-Output Database (WIOD; see also Timmer, Dietzenbacher, Los, Stehrer, and De Vries, 2015). The specification of sectors is closely linked to the standard NACE Rev. 2 classification (Eurostat, 2008). We simulate the CaT and TPS regime under both calibrations.

The TPS regime outperforms a CaT that redistributes carbon revenues to households in a lump-sum manner in terms of output gains and welfare because of lower costs on the production side. From a sectoral perspective, our simulations suggest that CaT hurts

[1]Production sectors vary in their factor intensity, the use of intermediate inputs, and the contribution to final demand. Energy can be clean or brown. Following Heutel (2012), Annicchiarico and Di Dio (2015) and Annicchiarico, Correani, and Di Dio (2018), among others, emissions occur as a by-product of production and differ by sector. Firms in each sector can engage in costly abatement activities. Unabated emissions increase the stock of carbon in the atmosphere, which will ultimately result in a loss of production (see also Annicchiarico, Carattini, Fischer, and Heutel, 2022, for a discussion). The environmental module is analogous to Ernst, Hinterlang, Mahle, and Stähler (2023); see also Hinterlang, Martin, Röhe, Stähler, and Strobel (2023), for a detailed technical documentation of the base model and its derivation.

dirty sectors relatively more than under TPS. Benefits of cleaner sectors are larger under TPS than with CaT.

Given our finding that the main difference between both regimes stems from different uses of revenues from carbon pricing, we perform two additional simulations: Using the revenues to either decrease consumption or labor income taxes. In terms of output, we find that TPS still outperforms these alternatives. However, using revenues from CaT for labor tax reductions increases welfare most because it alleviates distortions on the production side and improves the income situation of all households. Our model therefore takes into account an important aspect of carbon pricing that deserves further attention: How can we protect the environment without placing too much burden on society or individual groups? In the end, policy instruments that achieve the following two objectives are the most promising: firstly, a reduction of distortions on the production side and, secondly, an even distribution of welfare gains or burdens. In our model, the labor tax reduction is capable to do so.

The remainder of the paper is structured as follows. We discuss related literature in Section 2. The model is described in Section 3 and its calibration in Section 4. The design and the results of our baseline simulation are described in Section 5. Section 6 concludes.

2 Related literature

Our research contributes to several strands of literature. Like many others, we examine climate policies using a DSGE model. Among others, Golosov, Hassler, Krusell, and Tsyvinski (2014), Hillebrand and Hillebrand (2019) and Van Der Ploeg and Withagen (2014) focus on optimal climate policy providing welfare optimal carbon tax paths in closed form. Due to the explicit formal derivation, they have to rely on a limited number of frictions. We focus on the evaluation of policy scenarios instead. More precisely, we compare CaT to TPS systems akin to the regimes implemented in Europe and China, respectively. Because we do not need to derive optimal policy explicitly, this allows us to use a much more complex economic environment with multiple interlinked production sectors along the lines of Baqaee and Farhi (2024) and Bouakez, Rachedi, and Santoro (2023). Our contribution to this literature is the introduction of an environmental module to such a framework. In addition to comparing two emissions pricing regimes, we also compare different recycling options for the revenues of the employed climate policy.

Specifically, we use a dynamic production network model along the lines of Hinterlang et al. (2022). Production sectors vary in their factor intensity, the use of intermediate inputs, and the contribution to final demand. Energy is a specific consumption and/or intermediate input good that is more difficult to substitute than the other goods. Following Heutel (2012), Annicchiarico and Di Dio (2015) and Annicchiarico et al. (2018), among others, emissions occur as a by-product of production and differ by sector. Firms in each sector can engage in costly abatement activities. Unabated emissions increase the stock of carbon in the atmosphere, which can ultimately result in a loss of production (see also Annicchiarico et al., 2022, for a discussion). The environmental module is analogous to Ernst et al. (2023) and Hinterlang (2023).[2] We calibrate the model once to the EU-27

[2]See also Hinterlang et al. (2023), for a detailed technical documentation of the base model and its derivation.

plus UK (EU28) and once to China (CHN). We confirm several of the findings discussed about TPS being more output and abatement-friendly. CaT, in which carbon revenues are redistributed to households, tends to be the preferred policy of those who may otherwise face (wage) income losses resulting from carbon pricing. In addition, we are able to show that TPS is equivalent to a CaT regime in which the carbon revenues are redistributed to firms based on output.

Fischer (2001) and Fischer and Springborn (2011) study the effects of CaT and TPS regimes in a static RBC-type framework neglecting environmental damages (they discuss intensity targets, to which TPS effectively belongs). The authors find that a CaT regime has a countercyclical effect and reduces fluctuations over the business cycle compared to a TPS scheme. They point out that TPS increases the incentive to use clean factor inputs and/or invest into abatement. This favors production output, at the expense of welfare when neglecting production damage from pollution, however. Heutel (2012) employs a dynamic framework to analyze a CaT regime (neglecting the labor supply channel). He finds that, in an optimal policy scenario, emissions caps should be relaxed during boom phases because emissions reduction is cheaper in a recession. This result suggests that a TPS regime has larger positive welfare effects over the business cycle because countercyclical caps are introduced by construction. Goulder, Hafstead, and Williams (2016) show that TPS distorts factor markets less because it is a smaller implicit tax on factors of production and, thereby, more output friendly, which we also find. Holland, Hughes, and Knittel (2009) and Abrell, Rausch, and Streitberger (2019) show that the use of carbon pricing revenues is essential (recent related literature is discussed below), and that TPS can be considered to be a combination of an output subsidy and an input (carbon) tax. We dig deeper into this issue in the present paper.

More recently, Becker (2023), Goulder, Long, Qu, and Zhang (2023) and Zhang, Chen, and Tanaka (2018) explore the differences between a CaT and a TPS system in a dynamic setup. However, these studies only consider a partial equilibrium with investment costs as the only feedback mechanism to the broader economy. They find that TPS not only prices carbon of the dirtier producers but also subsidizes production of the cleaner ones as they can sell emissions permits. The studies consistently show that the blocked output-reduction channel and/or the output subsidy differs noticeably from a CaT system. Disregarding the business-cycle effects of the systems, we contribute to this literature by investigating the effects in a multi-sector DSGE-framework allowing for free allocation of emissions allowances. In addition, Pizer and Zhang (2018) discuss the implementation of the Chinese TPS pointing to potential inefficiencies. In order to reach a predetermined emissions reduction, authorities must have a wide knowledge of the underlying economic structure and the impact of their policies. Wang, Pizer, and Munnings (2022) investigate how price floors can be used to mitigate some of the disadvantages of TPS and the associated uncertainty regarding emissions. Fischer, Goulder, and Qu (2024) discuss different TPS schemes and their interaction with a variety of overlapping policies, including subsidies to renewables and taxes on electricity.

We also contribute to the literature addressing questions about whether or not emission allowances should be auctioned or distributed for free and about the appropriate use of carbon revenues. Studies such as Böhringer and Lange (2005) find that output-based allocations distort the economy towards higher output levels at the expense of leisure. Grandfathering (i.e. the costless allocation of permits based on previous emissions) creates an additional distortion through increased social costs of output. Fischer and Fox (2007) compare output-based allocation schemes to permit auctions with tax rebate. Here output-based allocation of permits represents a special case. They highlight the importance of additional tax distortions in assessing the relative performance of either allocation mechanism. Among others, Barrage (2020) examines optimal carbon taxation in presence of distortionary taxation and government spending, pointing out trade-offs between carbon taxation, overall economic activity as well as tax revenue. Forni and Kiarsi (2023) extend this framework by introducing monetary policy. Bartocci, Notarpietro, and Pisani (2024) find that a policy mix between reduced labor taxes and subsidies to renewable energy sectors can mitigate the adverse effects of carbon taxation. Hinterlang et al. (2022) further discuss the effects of using different environmental or energy taxes to lower labor income taxes in a model with production networks. Jondeau, Levieuge, Sahuc, and Vermandel (2022) consider subsidies to an abatement goods sector. This body of research suggests that the effects of carbon revenues recycling need to be considered. When focusing on efficiency in terms of output, carbon tax revenues can and should be used to decrease other distortionary taxes, opposing lump-sum transfers. We find that using carbon revenues to reduce labor income taxes is close to the TPS regime in terms of output and welfare effects. It may, however, be somewhat better in terms of redistribution, which confirms the findings by Annicchiarico, Battles, Di Dio, Molina, and Zoppoli (2017).

3 The model

We build a multi-sector model along the lines of the model presented by Hinterlang et al. (2023). Time t is discrete and runs forever. The model economy comprises $s \in \mathcal{S} = \{1, \ldots, S^{NE}, S^{E}, \ldots, S\}$ production sectors, including non-energy and energy goods, ranging from sectors 1 to S^{NE} and from S^{E} to S, respectively. In what follows, we will assume that there is only one energy sector in our economy, i.e. $S^{E} = S$. Introducing more energy sectors would be straightforward but would not generate any additional insight. Therefore, we rather keep it simple with one energy sector. Moreover, there are consumption, investment, and intermediate goods retailers, two types of households (optimizers and rule-of-thumb households, RoTs henceforth), as well as a fiscal authority. Both types of households receive income from providing labor. Optimizers additionally rent out physical capital to sectoral goods producers and obtain firm profits. Labor and capital are imperfectly mobile across sectors. Sectoral output is transformed into bundles of consumption, investment, and intermediate goods. This is accomplished by perfectly competitive retailers. Besides renting capital and labor from households, firms purchase intermediate input bundles. There is a representative firm in each sector that sets its price equal to marginal costs. Sectors are heterogeneous with respect to factor intensities. Production causes emissions, which may differ across sectors. Firms can invest in costly abatement technologies and face production damage resulting from pollution. A fiscal authority runs a balanced budget by levying or paying out lump-sum transfers to both types of households and taxing income from labor income and consumption as well as emissions. Throughout the paper, quantity variables will be expressed in per capita terms, unless otherwise indicated. In what follows, we will describe the economy in more formal detail.

3.1 Households

Following Gali, Lopez-Salido, and Valles (2007), we assume that the economy is populated by a share $\mu \in [0, 1)$ of liquidity-constrained RoT consumers, who do not participate in asset markets and consume their entire income each period, and a remaining share $(1-\mu)$ of capital and firm owners (optimizers). They are labeled by the subscript $i \in \{o, r\}$ for optimizing and RoT households, respectively. The distinction between these two types of households allows us to compare the two carbon pricing systems in terms of their distributional effects.[3] Following Jaimovich and Rebelo (2009), the utility function of each household in group i at time t is given by

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

where $X_{i,t} = X_{i,t-1}^{1-\gamma^{ghh}} \cdot C_{i,t}^{\gamma^{ghh}}$, which makes preferences non-time-separable in consumption C_t^i and labor N_t^i of a type-i household.[4] The parameter $\sigma \geq 0$ denotes the inverse of the elasticity of intertemporal substitution and $\kappa_{i,N}$ measures the relative weight of the disutility of labor. $\mathbb{E}_0$ is the expectations operator $\mathbb{E}_t$ at time $t = 0$. The choices of the optimizers are subject to the budget constraint

$$(1+\tau_t^c) C_t^o + P_t^I I_t^o = (1-\tau_t^w) w_t N_t^o + r_t^k K_{t-1}^o + TR_t^o + \sum_{s \in \mathcal{S}} \Pi_{s,t}, \tag{2}$$

while the RoT's budget constraint is

$$(1+\tau_t^c) C_t^r = (1-\tau_t^w) w_t N_t^r + TR_t^r. \tag{3}$$

Defining P_t^C as the CPI of consumption goods and $\tilde{P}_t^I$ as the nominal price of a basket of investment goods, I_t^i, we get $P_t^I = \tilde{P}_t^I / P_t^C$ as the real price of the latter resulting from an investment goods basket that can be different to the consumption goods basket. w_t is the real wage rate, r_t^k the return on physical capital holdings K_t^i. $\Pi_{s,t}$ is the profit of the representative firm in sector s. The average tax rate on the consumption good is τ_t^c, and the average labor tax rate is τ_t^w. TR_t^i are lump-sum transfers from (or payments to) the government (if negative). Aggregation across households implies $x_t = \mu \cdot x_t^r + (1-\mu) \cdot x_t^o$ for $x \in \{C, N, TR\}$ and $x_t = (1-\mu) \cdot x_t^o$ for $x \in \{I, K, \Pi\}$ (see Stähler and Thomas, 2012).

[3] At first sight, a TPS is less regressive than a CaT, because the implicit output subsidy dampens consumer price increases. Adding household heterogeneity in terms of spending patterns, through non-homothetic preferences, (see Känzig, 2023), this effect could even be amplified. However, in our model distributional effects are driven by the income side.

[4] These preferences nest as special cases the two classes of utility functions most widely used in the business cycle literature: If $\gamma^{ghh} = 1$ one gets preferences of the class discussed in King, Plosser, and Rebelo (1988). If $\gamma^{ghh} = 0$ the preferences resemble those proposed by Greenwood, Hercowitz, and Huffman (1988).

3.2 Labor and capital supply

We follow Bouakez et al. (2023) in assuming that the household's total labor supply N_t is a constant elasticity of substitution (CES) function of the labor provided to each sector $N_{s,t}$, i.e.

$$N_t = \left[\sum_{s \in \mathcal{S}} \psi_{N,s}^{1-\nu_N} N_{s,t}^{\nu_N} \right]^{\frac{1}{\nu_N}},$$

where $\psi_{N,s}$ is the weight attached to labor provided to sector $s \in \mathcal{S}$. We drop the index $i \in \{o, r\}$ for notational convenience as this analogously holds for optimizing and RoT households. The parameter ν_N is closely related (but not equal to) the elasticity of substitution of labor across sectors, capturing the degree of labor mobility. The real aggregate wage rate w_t associated with this CES aggregator is a function of the (weighted) sectoral wages $w_{s,t}$:

$$w_t = \left[\sum_{s \in \mathcal{S}} \psi_{N,s} w_{s,t}^{-\frac{\nu_N}{(1-\nu_N)}} \right]^{-\frac{(1-\nu_N)}{\nu_N}}. \tag{4}$$

In equilibrium, the optimal allocation of labor across sectors follows the first-order condition

$$N_{s,t} = \psi_{N,s} \left(\frac{w_{s,t}}{w_t} \right)^{-\left(\frac{1}{1-\nu_N}\right)} N_t \quad \forall s \in \mathcal{S}. \tag{5}$$

An analogous proceeding for the capital supply yields the first order condition

$$K_{s,t} = \psi_{K,s} \left(\frac{r_{s,t}^K}{r_t^K} \right)^{-\left(\frac{1}{1-\nu_K}\right)} K_t \quad \forall s \in \mathcal{S}, \tag{6}$$

and the aggregate return on capital is

$$r_t^K = \left[\sum_{s \in \mathcal{S}} \psi_{K,s} (r_{s,t}^K)^{-\frac{\nu_K}{(1-\nu_K)}} \right]^{-\frac{(1-\nu_K)}{\nu_K}}. \tag{7}$$

3.3 Consumption and Investment-goods retailers

Households demand bundles of consumption and investment goods C_t and I_t, which are traded at prices P_t^C and $\tilde{P}_t^I$, respectively. Again, we drop the index $i \in \{o, r\}$ for convenience. Following Hinterlang et al. (2022), the consumption goods bundle is divided into energy and non-energy goods bundles C_t^E and C_t^{NE}. They are traded at prices P_t^{CE} and P_t^{CNE}. The production technology of a perfectly competitive, representative retailer that bundles energy and non-energy consumption bundles is given by

$$C_t = \left[\psi_C^{1-\sigma_C} (C_t^{NE})^{\sigma_C} + (1-\psi_C)^{1-\sigma_C} (C_t^E)^{\sigma_C} \right]^{\frac{1}{\sigma_C}}.$$

The parameters ψ_C and σ_C determine the consumption utility value and control the elasticity of substitution between energy and non-energy consumption bundles. The optimization problem in CPI-deflated real terms can be written as

$$\max_{C_t^E, C_t^{NE}} P_t^C C_t - P_t^{C^{NE}} C_t^{NE} - P_t^{C^E} C_t^E.$$

Taking into account the bundling technology, the first-order conditions are

$$C_t^{NE} = \psi_C \left(\frac{P_t^{C^{NE}}}{P_t^C} \right)^{-\frac{1}{(1-\sigma_C)}} C_t \quad \text{and} \quad C_t^E = (1-\psi_C) \left(\frac{P_t^{C^E}}{P_t^C} \right)^{-\frac{1}{(1-\sigma_C)}} C_t. \tag{8}$$

Plugging these expressions into the constant elasticity of substitution aggregator shows that P_t^C is equal to the weighted sectoral consumption good prices. The production technologies of the perfectly competitive, representative retailers that bundle non-energy consumption goods are

$$C_t^{NE} = \left[\sum_{s \in \mathcal{S}^{NE}} \psi_{C^{NE},s}^{1-\sigma_{C^{NE}}} (C_{s,t})^{\sigma_{C^{NE}}} \right]^{\frac{1}{\sigma_{C^{NE}}}}. \tag{9}$$

The elasticity of substitution for non-energy goods is $\sigma_{C^{NE}}$, and the parameter governing the consumption utility value is $\psi_{C^{NE},s}$. Profit maximization implies the following first-order condition

$$C_{s,t} = \psi_{C^{NE},s} \left(\frac{P_{s,t}}{P_t^{C^{NE}}} \right)^{-\frac{1}{(1-\sigma_{C^{NE}})}} C_t^{NE}, \quad \forall s \in \mathcal{S}^{NE}, \tag{10}$$

where $P_{s,t}$ is the CPI-deflated producer price of sectoral good $s \in \mathcal{S}$. As there is only one energy sector, it holds that $C_t^E = C_{S,t}$ and $P_t^{C^E} = P_{S,t}$. For investment goods, we assume an analogous bundling technology in line with Bouakez et al. (2023), i.e.

$$I_t = \left[\sum_{s=1}^{S} \psi_{I,s}^{1-\sigma_I} I_{s,t}^{\sigma_I} \right]^{\frac{1}{\sigma_I}}, \tag{11}$$

where the investment goods bundler maximizes $\max_{I_{s,t}} P_t^I I_t - \sum_{s=1}^S P_{s,t} I_{s,t}$. The derivation is equivalent. The price index (relative to CPI) is thus given by

$$P_t^I = \left[\sum_{s=1}^{S} \psi_{I,s} (P_{s,t})^{-\frac{\sigma_I}{(1-\sigma_I)}} \right]^{-\frac{(1-\sigma_I)}{\sigma_I}}. \tag{12}$$

3.4 Production

In each sector $s \in \mathcal{S}$, there is a representative firm that produces a sectoral final good $y_{s,t}$ by transforming labor, $N_{s,t}$, capital, $K_{s,t-1}$, and a bundle of intermediate inputs, $H_{s,t}$. The sector-specific final good $y_{s,t}$ is sold to households and investors according to the consumption and investment demand baskets previously described at a price $P_{s,t}$. Formally, the production technology of a representative firm in sector s exhibits constant returns to scale and is given by

$$y_{s,t} = \left[1 - D\left(M_t\right)\right] \varepsilon_{s,t} \left(K_{s,t-1}^{1-\alpha_{N,s}} N_{s,t}^{\alpha_{N,s}}\right)^{\alpha_{H,s}} \left(H_{s,t}\right)^{1-\alpha_{H,s}}, \tag{13}$$

where $\varepsilon_{s,t}$ is total factor productivity, the α's determine factor intensity and $D\left(M_t\right)$ is a damage function that positively depends on the world emissions stock M_t. We assume that emissions-induced damage is either zero or that it is given by $D\left(M_t\right) = \gamma_0 + \gamma_1 \cdot M_t + \gamma_2 \cdot M_t^2$ (see, e.g., Heutel, 2012). Emissions are a by-product of production, taking the form $Z_{s,t} = \kappa_{s,t} \cdot (1 - U_{s,t}) \cdot y_{s,t}$ where $\kappa_{s,t} \in [0, \infty)$ depicts the emissions intensity before abatement $U_{s,t} \in [0, 1)$. Costly abatement is denoted by $U_{s,t}$, with the abatement cost function given by $C\left(U_{s,t}\right) = \phi_1 \cdot U_{s,t}^{\phi_2} \cdot y_{s,t}$, where $\phi_1 > 0$ and $\phi_2 > 1$ (see Annicchiarico and Di Dio, 2015, Annicchiarico et al., 2018, and Annicchiarico and Diluiso, 2019, for a discussion). Cost minimization yields the following first-order conditions for labor, capital and intermediate inputs:

$$w_{s,t} = \alpha_{H,s} \cdot \alpha_{N,s} \cdot mc_{s,t} \cdot \frac{y_{s,t}}{N_{s,t}}, \tag{14}$$

$$r_{s,t}^k = \alpha_{H,s} \cdot (1 - \alpha_{N,s}) \cdot mc_{s,t} \cdot \frac{y_{s,t}}{K_{s,t-1}}, \tag{15}$$

$$P_{s,t}^H = (1 - \alpha_{H,s}) \cdot mc_{s,t} \cdot \frac{y_{s,t}}{H_{s,t}}, \tag{16}$$

where $P_{s,t}^H$ is the CPI-deflated real price of these inputs and $mc_{s,t}$ are real marginal production costs in each sector. Abatement is determined by

$$\phi_1 \cdot \phi_2 \cdot U_{s,t}^{\phi_2 - 1} = P_t^{em} \cdot \kappa_{s,t}, \tag{17}$$

where the price per unit of emission is the same across sectors. For $P_t^{em} = 0$, it holds that $U_{s,t} = 0$ because firms do not take into account the pollution externality as it is costless from the individual firm's perspective. Under flexible prices, it holds that

$$P_{s,t} = \tilde{mc}_{s,t}, \tag{18}$$

with

$$\tilde{mc}_{s,t} = mc_{s,t} + EMC_{s,t}. \tag{19}$$

Hence, marginal costs relevant for the pricing decision also include marginal abatement costs and emissions taxes, $EMC_{s,t}$ (marginal costs relevant for pricing only equal marginal factor input costs whenever the price per emission is zero; see Annicchiarico and Di Dio, 2015). In detail, this marginal cost component is given by

$$EMC_{s,t} = \phi_1 \cdot U_{s,t}^{\phi_2} + P_t^{em} \cdot \left(\kappa_{s,t} \cdot (1 - U_{s,t}) - \iota \cdot \tilde{\kappa}_{s,t}\right), \tag{20}$$

where ι is an indicator function which takes the value one under the Chinese TPS and zero otherwise. Hence, the marginal environmental costs per unit of sectoral output equal the sum of abatement costs and the price that has to be paid for unabated emissions. These amount to $P_t^{em} \cdot \kappa_{s,t} \cdot (1 - U_{s,t})$ for the European CaT system. Firms have to pay for all unabated emissions. Under the Chinese TPS, firms receive $\tilde{\kappa}_{s,t}$ emissions allowances for each output unit produced. Thus, $\tilde{\kappa}_{s,t}$ is the legally determined (potentially sector-specific) average emissions intensity. Certificates for per-unit emissions beyond this threshold have to be purchased. If actual emissions intensity is below this threshold, firms can sell certificates. Everything else equal, this reduces the direct emissions cost in the Chinese system from the firms' perspective. Hence, firms have a lower incentive to reduce output relative to the CaT system.

The lower marginal cost and the resulting higher incentive to produce translate into a higher allowance price under TPS than in the European CaT if identical emissions targets are to be realized. The higher allowance price under TPS stimulates higher abatement activities than under CaT (see equation (17)). In the end, any emissions reduction can be achieved under TPS with a legally determined average emissions intensity $\tilde{\kappa}_{s,t}$ lower than (or equal to) the average emissions intensity that would result under CaT. Essentially, lower marginal costs under TPS encourage firms to reduce emissions more through abatement instead of output reduction as under CaT. TPS even incentivizes firms with emissions intensities below the threshold to produce more than they would do in the absence of any emissions pricing policy. The reason is that these firms are endowed for free with excess allowances. Their sale proceeds are then used to reduce producer prices given the zero-profit assumption.

What remains to be determined is factor demand for sector j-intermediates by sector $s \in \mathcal{S}$. Similar to the consumption goods structure, we assume that there exists an intermediate goods bundle $H_{s,t}$ that is made up of a non-energy goods bundle $NE_{s,t}$ (which, in turn, consists of sectoral inputs $NE_{s,j,t}$ with $j \in \mathcal{S}^{NE}$) as well as an energy good $E_{s,t} = E_{s,S,t}$ (as there is only one energy sector). Formally,

$$H_{s,t} = \left[(1-\alpha_{E,s})^{1-\sigma_H}(NE_{s,t})^{\sigma_H} + \alpha_{E,s}^{1-\sigma_H}(E_{s,t})^{\sigma_H}\right]^{\frac{1}{\sigma_H}}, \quad \forall s \in \mathcal{S}.$$

The sector-specific parameter $\alpha_{NE,s}$ weights non-energy and energy input bundles and σ_H determines the elasticity of substitution between those intermediate goods bundles. The optimization problem in CPI-deflated real terms, after accounting for possible taxes and subsidies, can be written as

$$\max_{E_{s,t}, NE_{s,t}} P^H_{s,t} H_{s,t} - P^{NE}_{s,t} NE_{s,t} - P^E_{s,t} E_{s,t}, \quad \forall s \in \mathcal{S}.$$

Taking into account the bundling technology, the first-order conditions $\forall s \in \mathcal{S}$ are

$$NE_{s,t} = (1-\alpha_{E,s}) \left(\frac{P^{NE}_{s,t}}{P^H_{s,t}}\right)^{-\frac{1}{(1-\sigma_H)}} H_{s,t} \quad \text{and} \quad E_{s,t} = \alpha_{E,s} \left(\frac{P^{E}_{s,t}}{P^H_{s,t}}\right)^{-\frac{1}{(1-\sigma_H)}} H_{s,t}. \tag{21}$$

The CES aggregator that bundles goods from non-energy producing sectors is

$$NE_{s,t} = \left[\sum_{j \in \mathcal{S}^N E} \psi_{NE,s,j}^{1-\sigma_{NE}} NE_{s,j,t}^{\sigma_{NE}}\right]^{\frac{1}{\sigma_{NE}}}, \quad \forall s \in \mathcal{S}.$$

Hence, the CES aggregator $NE_{s,t}$ aggregates the intermediate goods from sectors $j \in \mathcal{S}^{NE}$, after weighting them by the parameter $\psi_{NE,s,j}$ and taking into account the elasticity of substitution between those intermediate goods, which is determined by σ_{NE}. Optimization results in the first order condition

$$NE_{s,j,t} = \psi_{NE,s,j} \left(\frac{P_{j,t}}{P^{NE}_{s,t}} \right)^{-\frac{1}{(1-\sigma_{NE})}} NE_{s,t}, \quad \forall s \in \mathcal{S}. \tag{22}$$

Because there is only one energy sector $S^E = S$ in the economy and, therefore, $E_{s,t} = E_{s,S,t}$, it also holds that $P^E_{s,t} = P_{S,t}$.

3.5 Policy

The fiscal authority sets transfers to run a balanced budget each period:

$$TR_t = \tau^w_t \cdot w_t \cdot N_t + \tau^c_t \cdot C_t + (1-\iota) \cdot P^{em}_t \cdot \sum_{s \in \mathcal{S}} Z_{s,t}. \tag{23}$$

We assume that tax rates are set by policy makers and that, when they are changed, the transition is associated with an AR(1)-process. This implies that for all tax rates $X \in \{\tau^c_t, \tau^w_t\}$, it holds that $X_t/\bar{X} = \rho^x \cdot \left(X_{t-1}/\bar{X}\right)$, where the bar indicates the target (steady state) value and ρ^x is the autocorrelation parameter. The fiscal authority receives proceeds from pricing carbon only in the European CaT system (i.e. $\iota = 0$). In the Chinese system, emissions certificates are traded only between firms.

3.6 Market clearing and aggregation

Market-clearing in each sector then implies that

$$y_{s,t} = C^{i(s)}_{s,t} + I_{s,t} + \sum_{\tilde{s}=1}^{S} i(s)_{\tilde{s},s,t} + C\left(U_{s,t}\right),$$

where $i(s)$ denotes the indicator function $i(s) = \begin{cases} NE, & s \in \{1, \dots, S^{NE}\} \\ E, & else\,(s = S^E = S) \end{cases}$. Sectoral production must cover consumption, investment and intermediate goods demand, and abatement costs. Defining value added as what is left from production for consumption and investment, CPI-deflated aggregate value added can be expressed as

$$Y^{va}_t = C_t + P^I_t \cdot I_t, \tag{24}$$

where $C_t = \sum_{s=1}^{S} C^i_{s,t}$ and $I_t = \sum_{s=1}^{S} I^i_{s,t}$. Because the consumption and investment goods basket differ, we have to take into account the relative price of investment P^I_t.

Total economy-wide emissions per capita are given by $Z_t = \sum_{s \in \mathcal{S}} Z_{s,t}$ and the world emissions stock evolves according to

$$M_t = (1 - \rho^M) \cdot M_{t-1} + Z_t, \tag{25}$$

where $\rho^M \in (0,1)$ determines how fast additional emissions are relieved. If we take into account that European/Chinese emissions only make up a fraction of total world emissions, we could add Z_t^*, the emissions of the rest of the world, on the right-hand-side of the above equation. This would imply that domestic emissions reductions, Z_t, affect the emissions stock (and, thereby, damage) less. We abstract from this in our baseline simulations shown below but provide corresponding simulations in the appendix. All decisions must be such that they are mutually consistent and the above equations hold.

4 Calibration

The model calibration is structured into three segments. Initially, we establish general parameters that pertain to the aggregate economy, primarily sourced from existing scholarly work. Subsequently, we introduce a second parameter set that encapsulates the heterogeneity on the production side, enabling sector-specific characterizations in terms of factor intensities, input-output relationships and contributions to final demand. The third parameter cluster is dedicated to the model's environmental dimension, encompassing elements such as carbon intensity, abatement costs and the economic repercussions of emissions. We calibrate the model once to the EU-27 plus UK (EU28) and once to China (CHN). The parameters we have selected are detailed in the appendix, and we provide an in-depth discussion of these choices in the current section.

General parameters The model is calibrated to the quarterly frequency. We set the discount factor at $\beta = 0.992$, indicative of an annual interest rate of approximately 3.3%. The intertemporal elasticity of substitution is fixed at a conventional value of $\sigma_c = 2$. Along the lines of Coenen, Straub, and Trabandt (2013), the Frisch elasticity of labor supply is calibrated at 0.5 (i.e. $\Psi = 2$). The relative weight of labor disutility, κ_N, targets an aggregate labor supply of $\bar{N} = 0.33$. The share of rule of thumbers in the economy amounts to 0.3. An annual depreciation rate of 10% is adopted, a standard figure in the literature (as exemplified by Cooley and Prescott, 1995). Fiscal parameters are standard (see Gadatsch, Hauzenberger, and Stähler, 2016). Table A.2 summarizes our baseline calibration for these general parameters.

We have determined the substitution elasticities for goods across various sectors as follows: for the non-energy consumption basket, we adopt a value of 0.9, guided by the studies of Atalay (2017) and Baqaee and Farhi (2024). The investment goods basket is assumed to have a slightly lower elasticity of substitution, set at 0.75. For non-energy intermediate inputs, we select a value of 0.3, which falls within the range suggested by Bouakez et al. (2023), Atalay (2017) and Baqaee and Farhi (2024). The elasticity of substitution between energy and non-energy goods, both for consumption and intermediate inputs, is set at 0.27 and 0.1, respectively. For labor and capital substitution elasticities, we follow Bouakez et al. (2023), adopting a value of 2. Antoszewski (2019) provides a critical examination of these choices. Table A.3 summarizes the selected elasticities.

Sector-specific production parameters On the production side, we differentiate among $S = 11$ sectors, based on the NACE Rev. 2 classification. Our sectoral delineation follows Ernst et al. (2023). However, we further refine the role of energy to reflect its reduced substitutability with other intermediate inputs by constructing an aggregated energy composite sector, which includes the sectors mining and quarrying (B), manufacturing of oil and refined petroleum (C19), and supply of electricity, gas, steam, as well as air conditioning (D).

We introduce heterogeneities across sectors. Labor and capital are not perfectly mobile across sectors. Sectoral labor and capital weights, $\omega_{N,s}$ and $\omega_{K,s}$, are calibrated to match employment and capital shares, N_s/N and K_s/K, observed in empirical data. The production technology for intermediate goods varies by sector, allowing for diverse factor intensities. Each sector also contributes uniquely to final demand. We derive these parameters from the latest release of the World Input-Output Database (WIOD) using 2014 data, which includes socioeconomic accounts and input-output tables for 56 sectors across 43 countries. This data aids in determining $\omega_{N,s}$, $\omega_{K,s}$, $\alpha_{N,s}$, and $\alpha_{H,s}$, as well as inter-sectoral trade shares $\psi_{NE,s,j}$, the share of energy intermediates $\alpha_{E,s}$, and the sectoral shares in consumption and investment goods bundles, ψ_C, $\psi_{C^{NE},s}$, and $\psi_{I,s}$.

For convenience, we normalize relative prices to unity in the initial steady state. Sector-specific production parameters are consolidated in Table A.4, and Table A.5 displays the non-energy intermediate input linkages between sectors.

Environmental parameters We calibrate sector-specific CO2 emissions per unit of output using environmental accounts from the European Commission, consistent with the WIOD, and select 2014 as our reference year. Since observed data reflects emissions post-abatement, we align $(1 - U_{s,t})\kappa_t$ with the 2014 steady-state values.

The pollution stock decays linearly at a rate of $1 - \rho^{EM} = 0.9979$, following Heutel (2012) and Annicchiarico and Di Dio (2015). In the abatement cost function, we set $\phi_{2,s} = 2.8$ for all sectors as per Nordhaus (2008), while $\phi_{2,s} = 0.185$ follows Annicchiarico and Di Dio (2015). Our damage function suggests that a 10% increase in pollution stock relative to the baseline level would nearly double the sectoral output losses, loosely based on Kalkuhl and Wenz (2020). Although our model expresses pollution in arbitrary units, we scale coefficients to obtain consistent proportional output losses. Lowering the economic damage from emissions would diminish the reduction in damage and slow the productivity increase in our simulations, but the qualitative results remain unaffected as long as the damage is substantial. Due to data limitations, we assume uniform abatement costs and damage functions across sectors.

5 Analysis

We simulate the introduction of the European CaT and the Chinese TPS for both calibrations (China and EU28). To ensure comparability, we assume that the policy is set such that a predetermined path for aggregate economy-wide emissions $Z_{t\geq 0}$ is reached in both regimes. More precisely, we assume that the policy target is to reduce initial emissions by 20%, and that emissions follow an AR(1) process of the following form: $Z_t = \rho^Z \cdot Z_{t-1} + (1 - \rho^Z) \cdot \bar{Z}$, where $\rho^Z = 0.9$ and $\bar{Z}$ is the steady-state emissions level/target. Its initial value is reduced by 20%.[5]

[5]Note that, in practice, this emissions reduction can only be reliably achieved with CaT as it steers the emissions path directly. Under TPS this would require wide knowledge of the firms' reaction to the policy. In our analysis we abstract from this implementation issue.

In the European CaT system, this yields an endogenous carbon price path $P^{EM}_{t\geq 0}$ that is consistent with such an emissions path. Firms adjust via output reduction and higher abatement efforts. Revenues from emissions pricing are rebated to households on a per-capita basis. Changes in the fiscal budget resulting from second-round effects are taken of by lump-sum taxes levied on optimizers.

For the Chinese TPS system, we must bear in mind that aggregate economy-wide emissions intensity is given by

$$\kappa_t = \frac{Z_t}{\sum_{s\in\mathcal{S}} y_{s,t}}.$$

Hence, when assuming that the policy target is non-sector specific, policy chooses a sequence $\tilde{\kappa}_{s,t\geq 0} = \kappa^{pol}_{t\geq 0} \forall s$ that is consistent with a reduction in aggregate emissions $Z_{t\geq 0}$ under TPS. Each sector's representative firm receives $\kappa^{pol}_t \cdot y_{s,t}$ emissions allowances for free. Sectors with a lower emissions intensity sell their gratuitous unused allowances to sectors with an emissions intensity above the policy target. Thus, firms have no immediate incentive to reduce output in this system (for firms with below average emissions intensity, even the opposite holds). Instead, emissions reduction stems primarily from higher abatement spending. There will also be a sequence of prices $P^{EM}_{t\geq 0}$ consistent with a $\kappa^{pol}_{t\geq 0}$ that generates $Z_{t\geq 0}$. As we will see below, this looks different from the price sequence under CaT. Again, the fiscal budget is closed by lump-sum taxes levied on optimizers.

5.1 Macroeconomic and welfare effects of introducing CaT or TPS

Table 1 shows the long-run effects on selected aggregate macro variables of the two different carbon pricing regimes in Europe and China. Values are given in percent deviations from initial steady state. The transition dynamics are depicted in Figure 1, once for Europe (red and orange lines), and once for China (green and blue lines). Independent from the policy scenario and region, carbon pricing leads to an initial downturn due to higher marginal production costs. These increased costs reflect the increasingly priced emissions and translate into higher prices (see also equations (18) and (19) above) which, in turn, dampens demand and output. The downturn is eventually followed by an upturn due to lower damage from emissions. This reduction in emissions damages augments total factor productivity which may eventually dominate the distortions generated by carbon pricing. At least, it mitigates its negative impact. This confirms the results by Ernst et al. (2023), who analyze carbon pricing under CaT. We see that these general dynamics of carbon pricing also hold for TPS.[6]

If we compare the red to the orange (green to the blue) lines in Figure 1, we see the difference between TPS and CaT in Europe (China). Under TPS, output falls less during the transition. The same is true for consumption, investment and employment. Table 1 shows that in both regions TPS generates long-run output gains, while there are output losses under CaT. The latter are substantially higher in China.[7] Hence, the

[6] It is important to note here that we assume the emissions reduction to fully translate in an emissions stock and, thereby, damage reduction in our closed-economy framework. Due to, for example, carbon leakage (see Ernst et al., 2023, and Yu, Zhao, and Wei, 2020, for example), this is unlikely. We show simulation results of the closed-economy framework when ignoring damage reduction in Appendix B.

[7] We should note that the difference under CaT hinges on the assumption of an analogous damage

damage reduction resulting from 20% less emissions is not sufficient to overcompensate the increase in production costs under CaT in the end. Given the same emissions reduction of 20%, output falls less under TPS than under CaT. Hence, the carbon intensity has to fall more under TPS relative to CaT. Consequently, the carbon price is larger under TPS, which implies larger abatement efforts. These results are in line with Becker (2023) and Fischer and Springborn (2011), who also find lower output losses with an intensity target compared to a CaT.

Our analysis also reveals that an emissions reduction of 20% results in a lower carbon price in China than in Europe, both under TPS and CaT. The reason is that China has a higher average carbon intensity (relative to Europe), which makes an analogous price generate higher costs. In other words, a lower carbon price already incentivises a sufficient output reduction and/or abatement spending to achieve a 20% emissions reduction. Another perspective on this would be to see Europe ahead of China with a view to reducing emissions (given the calibration data described in the previous section). Hence, a further 20% reduction target would be more ambitious for Europe than for China translating into a higher allowances price.

Figure 2 shows the long-run sectoral effects of the two carbon pricing regimes for Europe (in blue) and for China (in red). We find that both policies affect the structure of the economy as carbon intensities differ. Under both regimes, dirty sectors tend to be negatively affected, while clean sectors are likely to benefit. The sectors with the highest carbon intensity include the energy sector (B_C19_D), manufacturing (C_{ETS}) and transport (H_{ETS}). Whereas service sectors have the lowest carbon intensity (J and M_N).

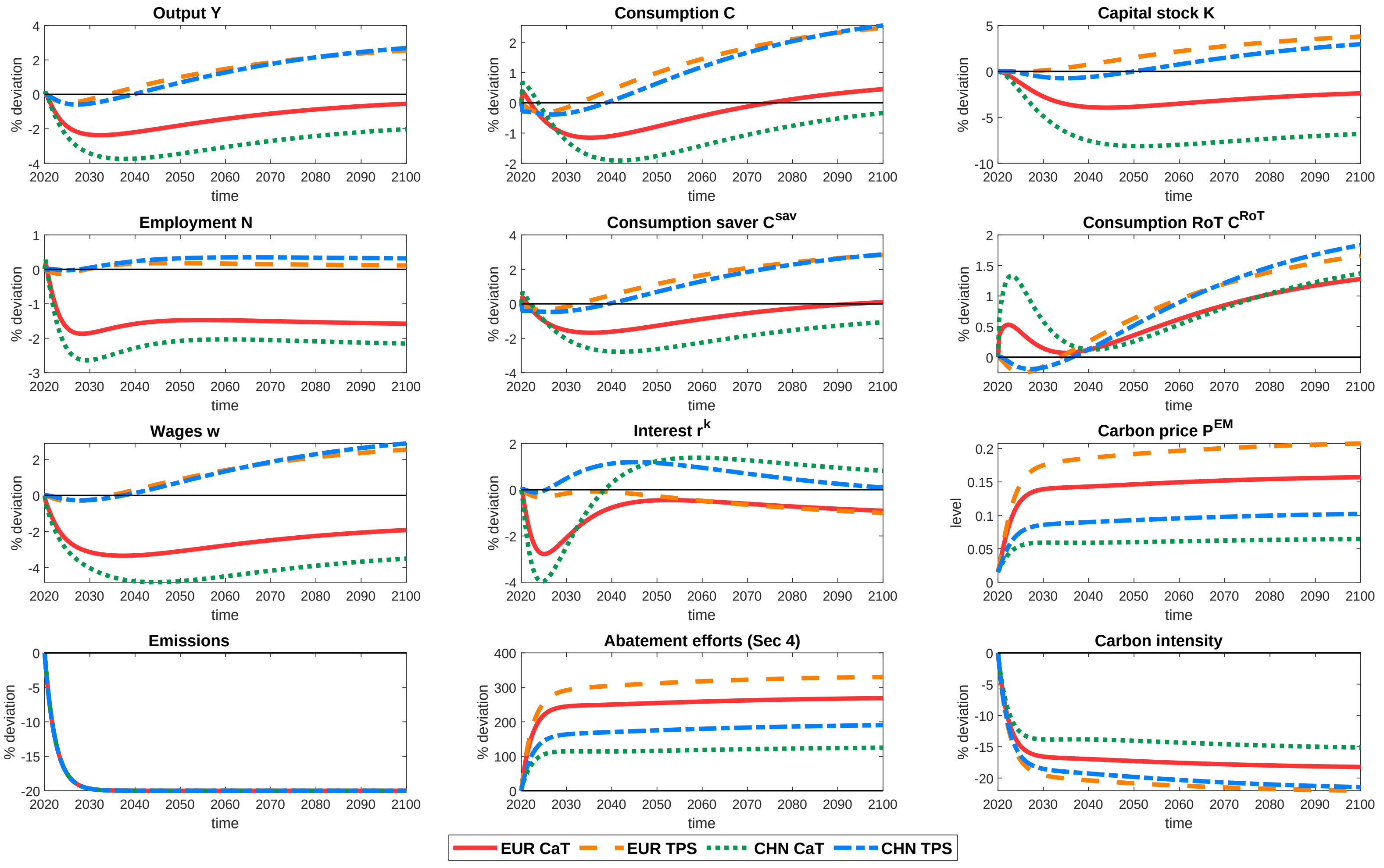
Table 1: Long-run effects

Scenario:	CaT in Europe	TPS in Europe	CaT in China	TPS in China
Output	-1.08	1.92	-2.62	1.93
Consumption	-0.13	1.85	-1.06	1.78
...of savers	-0.57	2.10	-1.88	1.96
...of RoTs	0.88	1.26	0.87	1.35
Investment	-2.66	3.36	-7.04	2.45
Hours	-1.56	0.07	-2.12	0.25
Wages	-2.38	1.95	-4.04	2.15
Emissions	-20.00	-20.00	-20.00	-20.00

Notes: Table shows long-run effects on selected aggregate macro variables of different carbon pricing regimes, in percent deviations from initial steady state.

reduction function in both regions. If damage reduction was higher in China, the long-run effects, would, of course be more positive there.

Figure 1: Implications for selected macroeconomic and environmental variables



Notes: Figure shows the effects of an emissions reduction of 20 % on macroeconomic and environmental variables under CaT and TPS in Europe (red and orange) and China (green and blue). Depicted is the transition until 2100. A figure with the transition to the final steady state is in the appendix.

Under TPS, cleaner sectors tend to benefit more and dirty sectors tend to lose less. The reason is straightforward. In both systems, there is a shift of relative producer prices in favor of cleaner goods. This increases demand for those goods. In case of TPS, this shift is boosted by the fact that sectors which produce with below-average emissions intensity can sell emissions allowances (see equation (18) in combination with (19) and (20)). Sectors with an above-average emissions intensity need to purchase these certificates but, as they also receive some certificates for free, they have to purchase less than under CaT (given equal allowance prices for the sake of comparison). Hence, firms in all sectors have less an incentive to reduce output than under CaT. Their higher propensity to produce translates into a higher demand for allowances and, thus, in a higher allowance price under TPS than under CaT. Therefore, the incentive for abatement spending is higher under TPS. Resulting changes in relative producer prices then imply a corresponding change in the economy's structure.

In terms of consumer welfare, TPS also tends to outperform CaT both in the long run and when taking into account the transition, at least for the average consumer. Table 2 depicts changes in steady-state consumption equivalents of both policies for optimizers, RoTs and the average household. In a pure steady-state comparison, both types of households benefit under both regimes (except Chinese optimizers, which we discuss below). The reason is that households' consumption increases, while labor falls (or increases only mildly).

If China introduces a carbon tax, optimizing households will lose out. Lower production reduces their wage and capital income, and higher per capita transfers from carbon pricing are not sufficient to compensate for this. However, the per capita transfers overcompensate the income losses of RoT consumers, as these only result from lower wage income. RoT consumers actually benefit more under CaT than under TPS, because welfare gains under TPS primarily result from higher wage income.[8] In contrast, optimizers benefit disproportionally from TPS because of their higher capital income. This shows that, under CaT, the government can use revenues from carbon pricing for re-distributional purposes even though output gains are lower (or even negative). Under TPS, this is not possible. However, Goulder et al. (2016) show that TPS benefits from a tax interaction effect (see also Bovenberg and Goulder, 1996, on such an environmental "double dividend" hypothesis). As employment and aggregate consumption are higher relative to CaT, increased tax revenue allows the fiscal authority to lower lump-sum taxes.[9]

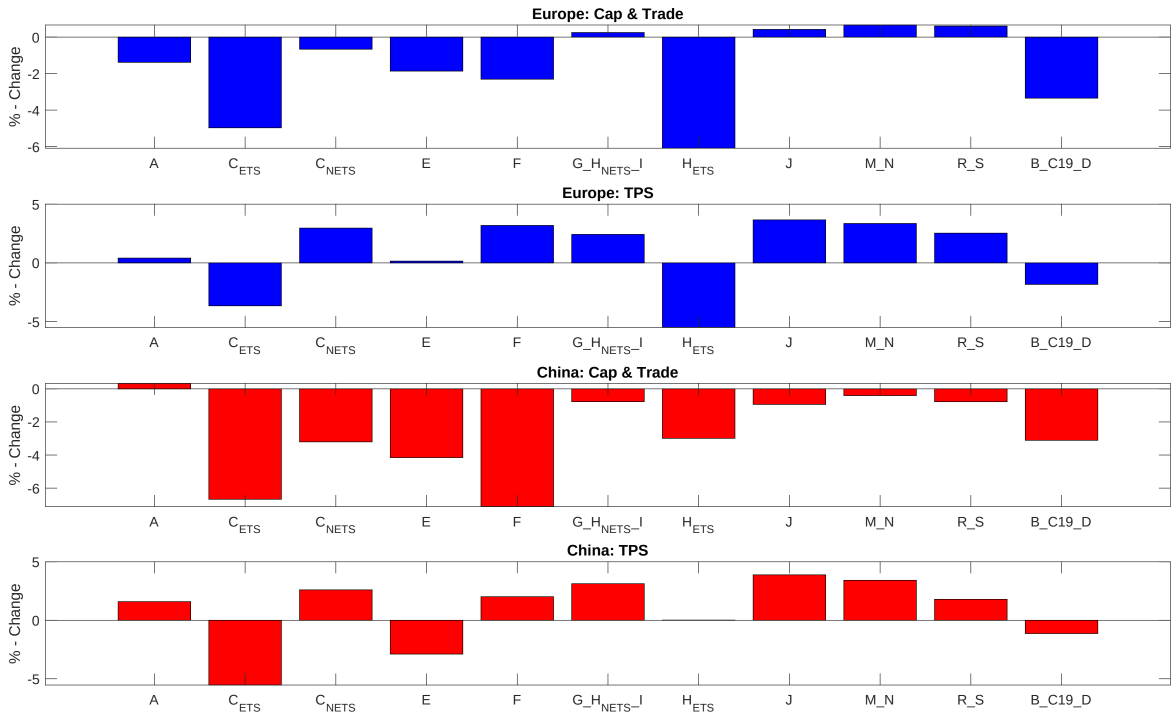
When taking into account the transition, welfare gains are much lower due to the adverse economic effects on impact and some time thereafter. This finding is already presented and described by Ernst et al. (2023), among others. While overall welfare increases, it takes time before the positive effects due to less emissions damage materialize.

At first glance, we are now left with the impression that the comparatively complicated TPS scheme outperforms the rather simple CaT system. In order to answer the question why, let us take a closer look at the TPS regime. Firms that receive emissions allowances

[8] This effect does not hold if all revenues from carbon pricing under CaT are paid to optimizers. In this case, they gain while RoTs lose. Conversely, if all revenues are paid to RoTs, optimizers' welfare further decreases (and may become negative even in Europe).

[9] In Appendix C, we show that, when neglecting this tax interaction effect (by setting labor and consumption tax rates to zero), CaT indeed mildly outperforms TPS by significantly reducing optimizers' welfare. Hence, the tax interaction effect is important. A different utility function and a higher emissions reduction target also shrink the welfare difference. However, it does not change the ranking.

Figure 2: Implications for long-run sectoral output



Notes: Figure shows the effects of an emissions reduction of 20 % on sectoral value added under CaT and TPS in Europe (blue) and China (red).

based on some average emissions intensity (determined by the government) maximize profits

$$\Pi_{s,t} = P_{s,t} \cdot y_{s,t} - w_{s,t} \cdot N_{s,t} - r^k_{s,t} \cdot K_{s,t-1} - P^H_{s,t} \cdot H_{s,t} - C\left(U_{s,t}\right) - \left[P^{em}_t \cdot \left(\kappa_{s,t} \cdot (1 - U_{s,t}) - \tilde{\kappa}_{s,t}\right)\right] \cdot y_{s,t}$$

by choosing labor, capital, intermediate inputs and abatement efforts. This yields the first-order conditions presented in Section 3.4 for $\iota = 1$. Now, imagine the government implements CaT but pays out revenues no longer to households, but to firms based on an average emissions intensity calculated analogously to the one under TPS. In this case, the profit function of firms becomes

$$\Pi_{s,t} = P_{s,t} \cdot y_{s,t} - w_{s,t} \cdot N_{s,t} - r^k_{s,t} \cdot K_{s,t-1} - P^H_{s,t} \cdot H_{s,t} - C\left(U_{s,t}\right) - \left[P^{em}_t \cdot \kappa_{s,t} \cdot (1 - U_{s,t})\right] \cdot y_{s,t} + TR^f_{s,t},$$

where $TR^f_{s,t} = \tilde{\kappa}_{s,t} \cdot y_{s,t}$ and carbon pricing-based transfers paid to households are set to zero for all t. It is straightforward to show that this also yields the first-order conditions presented in Section 3.4 for $\iota = 1$. Hence, apart from the mentioned implementation issues, the TPS is identical to a CaT system that pays out revenues from carbon pricing to firms proportionate to output. The distortions on the production side introduced by carbon pricing are, thus, relieved to some extent. This is not the case if revenues are used to finance lump-sum transfers to households. In that case, the distortions on the production side remain and are hardly relieved from distortion-free lump-sum payments on the demand side.

Table 2: Welfare effects

	Optimizers	RoTs	Aggregate
Steady state...			
EUR CaT	0.08	1.65	0.55
EUR TPS	1.70	0.79	1.43
CHN CaT	-0.88	2.10	0.01
CHN TPS	1.51	0.84	1.31
With transition...			
EUR CaT	-0.23	1.26	0.22
EUR TPS	0.73	0.31	0.60
CHN CaT	-0.77	1.81	0.00
CHN TPS	0.45	0.31	0.41

Notes: Table shows welfare implications of different carbon pricing regimes, expressed as consumption-equivalent gain for the respective household in line with Lucas (2003), in percentage deviations from initial steady state. The aggregate welfare effects are a population size-weighted average.

In the end, the comparison of the two regimes boils down to the question about the use of revenues from carbon pricing. Therefore, in the following subsection, we analyse how a CaT performs when its revenues finance tax reductions.

5.2 Macroeconomic and welfare effects of pricing carbon and reducing taxes

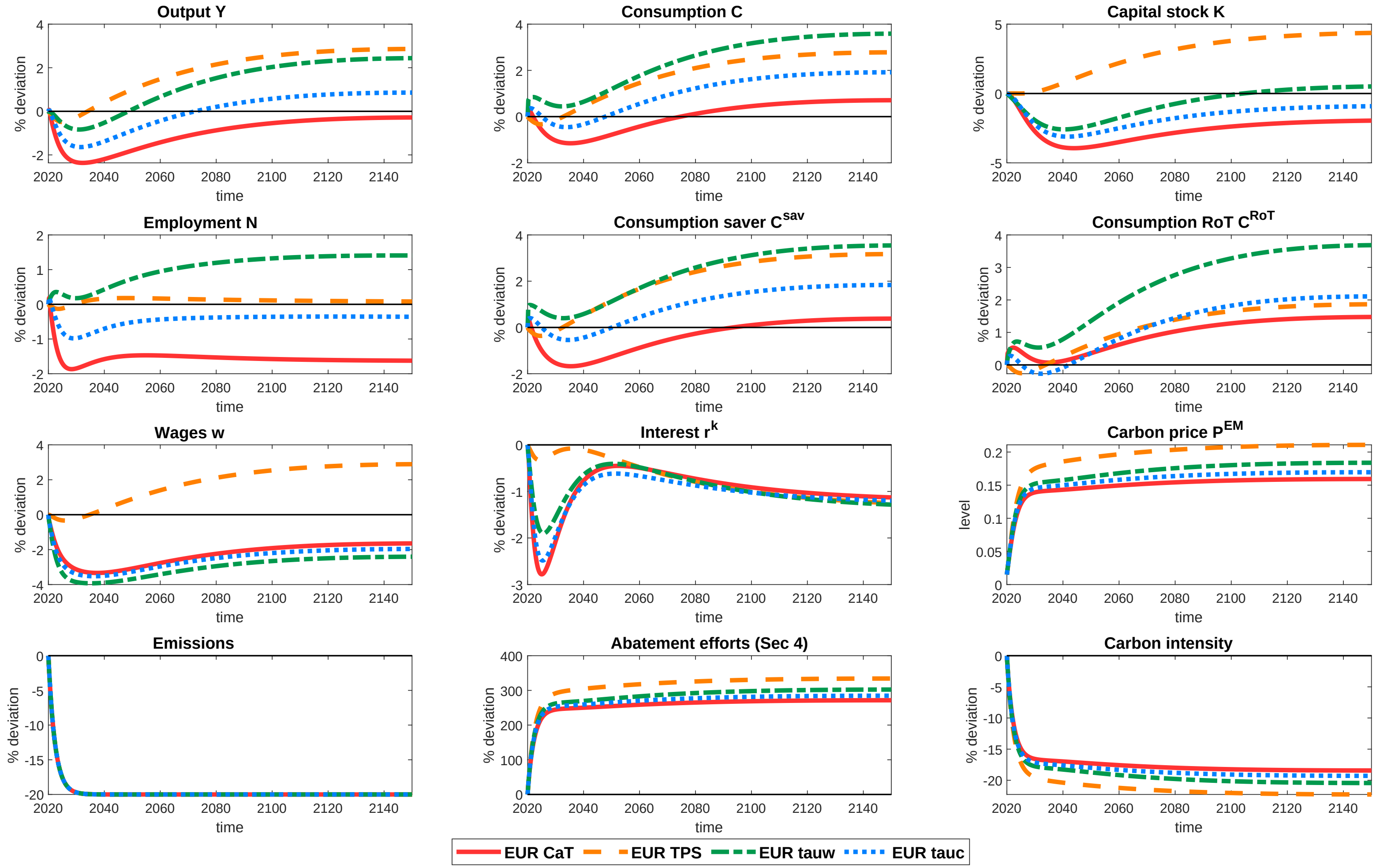
Instead of paying out the revenues from carbon pricing to either households or firms, we analyse the effects of using these revenues for a reduction of either labor or consumption taxes. The remaining simulation setup is analogous. We implement CaT with an emissions reduction of 20% while now reducing one of the taxes. Table 3 summarizes the long-run implications of such a policy change, while Figures 3 and 4 show the transition dynamics in Europe and China, respectively. For the sake of convenience, we repeat the graphs of our baseline CaT and TPS in these figures. Figure 5 shows the sectoral implication (in the long run), and Table 4 summarizes the welfare implications.

Consumption tax reductions alleviate the price increases for households associated with higher carbon price-induced production costs. While similar to a lump-sum transfer to households, the consumption tax reduction has some beneficial effects for capital investment. Expecting (future) consumption tax reductions increases the incentive for capital investment and augments medium-term income. From this, solely optimizers gain relative to a lump-sum transfer. This is confirmed in Table 3 and Figures 3 and 4. Overall, using carbon pricing revenue for a consumption tax reduction outperforms a CaT with lump-sum transfers in terms of output and consumption. However, they fall short of the TPS regime.

If wage tax is reduced, households accept lower gross wages, while at the same time their net income increases. This lowers firms' labor costs and reduces the cost increase caused by carbon pricing. Production becomes more labor intensive. In both regions output increases less than with a TPS. However, the gap to TPS is significantly smaller in Europe (in absolute terms) due to the overall lower costs of carbon pricing (see also Table 3). In contrast, average consumption increases most when labor taxes are reduced relative to any other scenario analyzed. This also holds for RoT consumers who gain disproportionately from the increase in net labor income which becomes effective almost immediately (see also Figures 3 and 4). The consumption gain of optimizers may be lower relative to a pure TPS (and in China they would prefer a TPS). Nevertheless, it is substantially higher in both regions than under CaT with lump-sum transfers. Moreover, consumption gains are more equally distributed between both types of households.

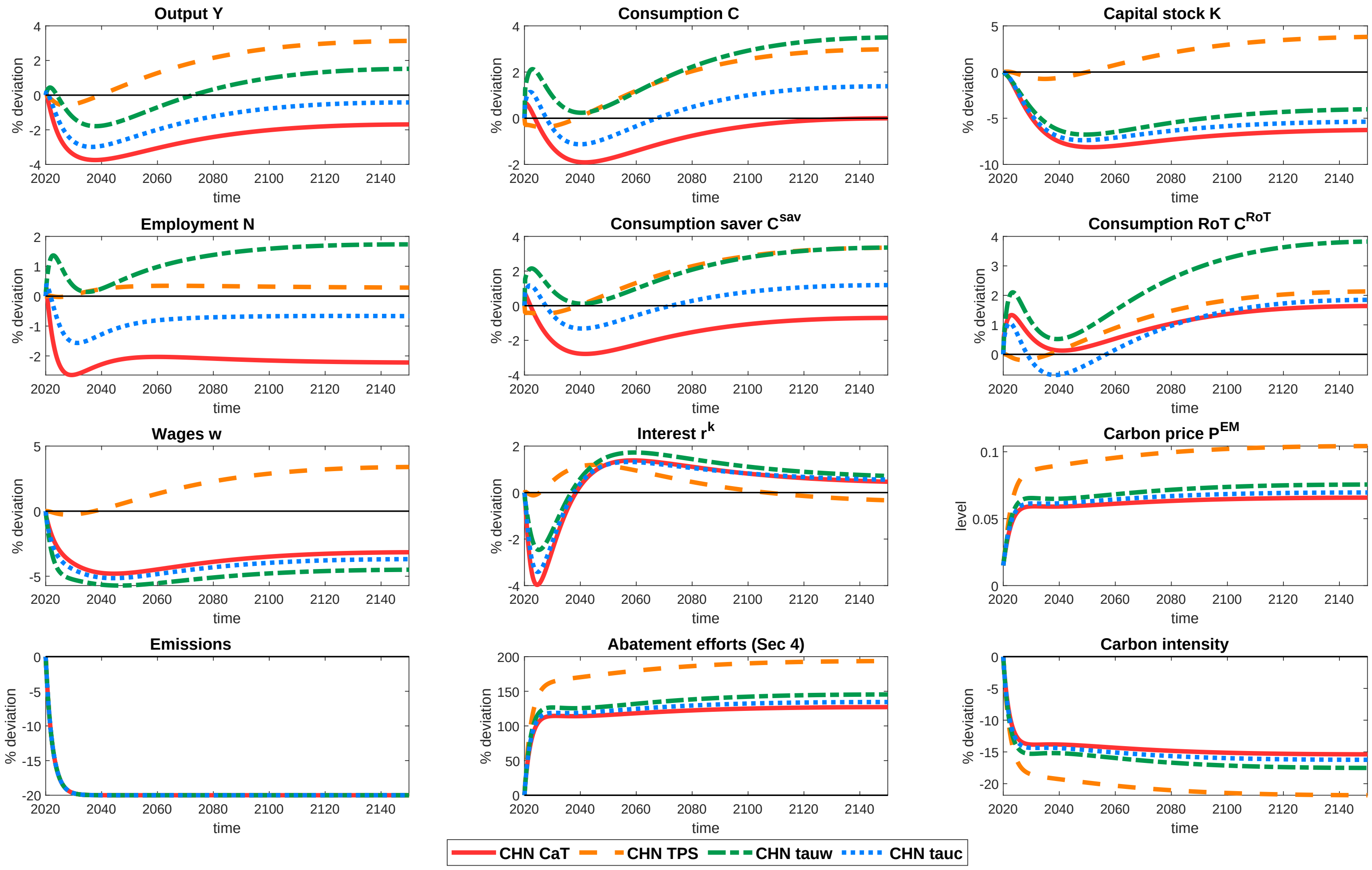
Figure 5 shows that CaT combined with a consumption tax reduction affects sectors similar to a CaT regime with lump-sum transfers. In contrast, the sectoral effects in case of CaT with labor tax reduction resemble more to a TPS. Dirty sectors generally lose, while clean sectors benefit. In addition, benefits are slightly tilted towards the labor-intensive sectors like the wholesale and retail trade, transportation and storage, accommodation and food sector ($G\_H_{NETS}\_I$) and the professional, scientific, technical, administrative and support services (M_N).

Figure 3: Implications for selected macroeconomic and environmental variables when reducing taxes (Europe)



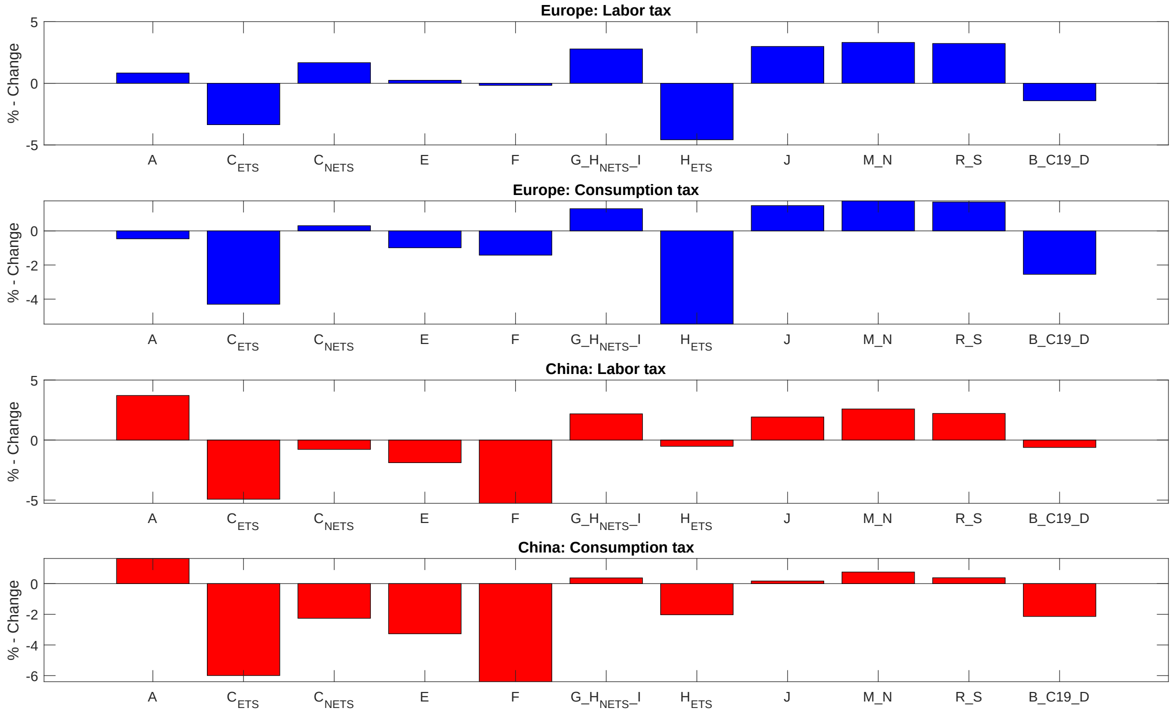
Notes: Figure shows the effects of an emissions reduction of 20 % on macroeconomic and environmental variables under CaT and combined with tax reductions in Europe.

Figure 4: Implications for selected macroeconomic and environmental variables when reducing taxes (China)



Notes: Figure shows the effects of an emissions reduction of 20 % on macroeconomic and environmental variables under CaT and combined with tax reductions in China.

Figure 5: Implications of CaT with tax reductions for long-run sectoral output



Notes: Figure shows the effects of an emissions reduction of 20 % on sectoral value added under CaT and tax reductions.

Table 4 summarizes the welfare effects of the two additional simulations with tax reductions. Given the consumption increase in both regions, it is not surprising that welfare gains are positive in the long run, for all household types. Welfare effects for optimizers are highest under CaT with labor tax reduction, followed by TPS (see Table 2). We note however, that this order changes in a pure steady state comparison. Then, TPS generates the highest welfare gains as the comparatively higher consumption losses at the beginning of the transition are not taken into account.

RoT households are also better off in case of CaT with labor tax reduction compared to TPS. However, they would still prefer the lump-sum transfers, although consumption gains are higher in case of a labor tax reduction (both with and without the transition). The reason is that substantially higher employment induced by the labor tax reduction goes along with higher disutility of labor. However, the welfare gains of this option are lowest for the optimizing households.

Table 3: Long-run effects of tax reductions

Scenario:	$\tau^w \downarrow$ in Europe	$\tau^c \downarrow$ in Europe	$\tau^w \downarrow$ in China	$\tau^c \downarrow$ in China
Output	1.23	-0.12	0.04	-1.59
Consumption	2.31	0.88	1.84	0.07
...of savers	2.24	0.77	1.67	-0.15
...of RoTs	2.47	1.12	2.24	0.58
Investment	-0.57	-1.80	-5.17	-6.31
Hours	1.02	-0.50	1.17	-0.85
Wages	-3.01	-2.64	-5.14	-4.47
Emissions	-20.00	-20.00	-20.00	-20.00

Notes: Table shows long-run effects on selected aggregate macro variables of different tax reduction regimes after carbon pricing, in percent deviations from initial steady state.

Table 4: Welfare effects of tax reductions

	Optimizers	RoTs	Aggregate
Steady state...			
EUR $\tau^w \downarrow$	1.31	1.55	1.38
EUR $\tau^c \downarrow$	0.79	1.17	0.90
CHN $\tau^w \downarrow$	0.79	1.40	0.97
CHN $\tau^c \downarrow$	0.16	0.96	0.40
With transition...			
EUR $\tau^w \downarrow$	0.77	0.87	0.80
EUR $\tau^c \downarrow$	0.41	0.65	0.48
CHN $\tau^w \downarrow$	0.66	0.96	0.75
CHN $\tau^c \downarrow$	0.17	0.65	0.31

Notes: Table shows welfare implications of different carbon pricing regimes, expressed as consumption-equivalent gain for the respective household in line with Lucas (2003), in percentage deviations from initial steady state. The aggregate welfare effects are a population size-weighted average.

Taken together, CaT with labor tax reduction yields the highest welfare gains for the average household (when including transition). It combines two important policy objectives. Firstly, it reduces distortions on the production side and secondly, it improves the income situation of both household types. CaT combined with a consumption tax reduction does not achieve the first objective. Nevertheless, it has the potential to redistribute the revenue from carbon pricing more equally between both types of households. This holds true for both regions compared to CaT with lump-sum transfers and in Europe also compared to TPS.

6 Conclusions

In this paper, we compare the economic and welfare implications of two carbon pricing policies, namely the European Cap and Trade (CaT) regime and the Chinese Tradeable Performance Standard (TPS) in a dynamic multi-sector general equilibrium TANK model. The former sets an economy-wide emissions target and forces firms to purchase sufficient certificates. The latter targets the average emissions intensity in the economy and requires firms with a higher intensity to either abate or buy emissions allowances from firms with lower-than-target intensities. We find that TPS outperforms a CaT that redistributes carbon revenues to households in a lump-sum manner in terms of output gains and welfare because of fewer distortions on the production side. Moreover, we show that TPS is equivalent to CaT when carbon pricing revenues are redistributed to firms proportionately to output. This rises the question about the appropriate use of revenues from carbon pricing under CaT. Ideally, the policy should fulfill two objectives: mitigating increased production costs and an equal distribution of welfare gains or burdens across household types. TPS alias CaT with output based subsidy fosters output most because it satisfies the former objective. However, optimizers benefit substantially more in terms of welfare than rule of thumbers. While using revenues from CaT for a consumption tax reduction can satisfy the second objective, it falls short of the former. Combining CaT with a labor tax reduction instead is capable of both. While output effects fall short of those under TPS, it yields the largest welfare gains for the average household. In addition, welfare benefits are distributed quite equally, only slightly favoring rule of thumbers. Hence, the paper addresses an important aspect for the acceptance of carbon pricing: how can we save the environment without placing too great a burden on society or individual groups? Focusing solely on the growth effect of carbon pricing falls short in this respect. The distribution of welfare gains or possible burdens among individual groups, should also be considered.

Appendix

In the appendix, we provide calibration details (Appendix A), additional simulation results when ignoring damage (Appendix B) and results when using a different utility function and setting labor and consumption taxes to zero (Appendix C).

Appendix A: Calibration details

Table A.1: Choice of regions and sectors

Region:	either EU plus UK (EU28) or China (CHN)
Sectors:	
1)	Agriculture, forestry and fishing
2)	Manufacturing (ETS)
3)	Manufacturing (Non-ETS)
4)	Water supply
5)	Construction
6)	Wholesale and retail trade, transport and storage (Non-ETS), accomodation & food
7)	Transport (ETS)
8)	IT and communication
9)	Prof., scient. and techn. & admin. and support services
10)	Arts, entertainment, recreation & oth. services
11)	Energy: Mining and quarrying, manufacturing of oil and refined petroleum, electricity, gas, steam and air conditioning supply

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

Table A.2: Baseline calibration of general parameters

Variable/Parameter	Symbol	Value
Discount factor	β	0.992
Elasticity of intertemporal substitution	σ	2.000
GHH parameter	γ	0.050
Inverse of Frisch elasticity of lab. supply	ζ	2.000
Labor disutility scaling	$\kappa_{o/r,N,EU28}$	3.808
Labor disutility scaling	$\kappa_{o/r,N,CHN}$	3.693
Share of RoTs	λ	0.3
Capital depreciation rate	δ^k	0.025
Consumption tax rate	$\bar{\tau}^c$	0.190
Labor tax rate	$\bar{\tau}^n$	0.300
AR(1) coefficient fiscal instruments	ρ^x	0.900

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

Table A.3: Baseline calibration of parameters determining the elasticity of substitution (EOS)

Symbol	Value	EOS	Determines EOS between...
σ_C	-2.704	0.270	*NE* & *E* consumption goods
$\sigma_{C^{NE}}$	-0.100	0.909	*NE* consumption goods
σ_I	-0.332	0.751	investment goods
ν_N	2.000	-1.000	labor across sectors
ν_K	2.000	-1.000	capital across sectors
$\sigma_{H,s}$	-9.000	0.100	*NE* & *E* intermediate input goods
$\sigma_{NE,s}$	-2.333	0.300	*NE* intermediate inputs

Notes: The table shows calibrated values for the parameters determining the EOS as described in the main text. *NE* and *E* refer to non-energy and energy, respectively. The EOS reported in column three is computed as $1 - 1/\sigma$, where $\sigma \in \{\sigma_C, \sigma_{C^{NE}}, \sigma_I, \nu_N, \nu_K, \sigma_{H,s}, \sigma_{NE,s}\}$.

Table A.4: Baseline calibration of sector-specific parameters

	$\alpha_{N,s}$	$\alpha_{H,s}$	$\alpha_{E,s}$	N_s/N	K_s/K	$\psi_{C^{NE},s}/\psi_C$ or $\psi_{C^E,s}/(1-\psi_C)$	$\psi_{I,s}$
Region: EU28							
1) Agriculture, forestry and fishing	0.665	0.420	0.049	0.070	0.061	0.037	0.004
2) Manufacturing (Non-ETS)	0.595	0.247	0.158	0.026	0.043	0.031	0.009
3) Manufacturing (NETS)	0.625	0.326	0.034	0.171	0.162	0.294	0.291
4) Water supply	0.476	0.412	0.284	0.010	0.055	0.024	0.001
5) Construction	0.745	0.387	0.028	0.088	0.082	0.021	0.427
6) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.673	0.516	0.046	0.342	0.254	0.448	0.069
7) Transport (ETS)	0.542	0.273	0.015	0.004	0.015	0.025	0.001
8) IT and communication	0.592	0.505	0.026	0.040	0.058	0.068	0.084
9) Prof., scient. and techn. & admin. and support services	0.721	0.551	0.027	0.173	0.113	0.043	0.101
10) Arts, entertainment, recreation & oth. services	0.732	0.589	0.065	0.063	0.051	0.078	0.005
11) Energy	0.300	0.261	0.522	0.013	0.106	1.000	0.008
Region: CHN							
1) Agriculture, forestry and fishing	0.950	0.586	0.030	0.287	0.050	0.132	0.011
2) Manufacturing (Non-ETS)	0.370	0.179	0.254	0.041	0.112	0.018	0.003
3) Manufacturing (NETS)	0.476	0.202	0.025	0.194	0.289	0.481	0.297
4) Water supply	0.641	0.352	0.306	0.001	0.011	0.008	0.000
5) Construction	0.639	0.231	0.035	0.101	0.017	0.003	0.627
6) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.513	0.531	0.043	0.195	0.112	0.228	0.028
7) Transport (ETS)	0.505	0.364	0.017	0.006	0.030	0.009	0.001
8) IT and communication	0.371	0.550	0.026	0.014	0.030	0.048	0.028
9) Prof., scient. and techn. & admin. and support services	0.684	0.387	0.015	0.022	0.025	0.014	0.004
10) Arts, entertainment, recreation & oth. services	0.839	0.460	0.043	0.107	0.160	0.089	0.000
11) Energy	0.383	0.284	0.586	0.033	0.164	1.000	0.001

Notes: The table shows calibrated values for sector-specific parameters as described in the main text. The values were computed by the authors based on the World Input-Output Database for the year 2014.

Table A.5: Input-Output matrix, $\psi_{H,s,j}$

	Consumer s										
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
Region: EU28											
1)	0.279	0.024	0.081	0.030	0.005	0.017	0.006	0.005	0.006	0.011	0.055
2)	0.096	0.415	0.126	0.078	0.130	0.031	0.017	0.027	0.027	0.040	0.093
3)	0.302	0.137	0.468	0.109	0.239	0.181	0.124	0.139	0.093	0.134	0.131
4)	0.018	0.061	0.012	0.277	0.010	0.013	0.006	0.008	0.011	0.027	0.131
5)	0.025	0.029	0.013	0.063	0.312	0.041	0.019	0.022	0.028	0.038	0.088
6)	0.169	0.177	0.164	0.132	0.131	0.412	0.484	0.123	0.133	0.151	0.156
7)	0.007	0.020	0.007	0.032	0.005	0.021	0.115	0.009	0.020	0.018	0.058
8)	0.017	0.029	0.022	0.062	0.020	0.060	0.041	0.375	0.110	0.104	0.076
9)	0.077	0.088	0.098	0.181	0.139	0.205	0.178	0.259	0.545	0.241	0.154
10)	0.009	0.020	0.009	0.037	0.009	0.019	0.010	0.033	0.025	0.236	0.059
Region: CHN											
1)	0.361	0.039	0.110	0.035	0.017	0.068	0.002	0.007	0.025	0.013	0.059
2)	0.160	0.496	0.170	0.115	0.472	0.021	0.029	0.022	0.101	0.114	0.132
3)	0.348	0.168	0.556	0.231	0.244	0.324	0.384	0.409	0.425	0.451	0.244
4)	0.008	0.029	0.004	0.181	0.005	0.007	0.004	0.004	0.004	0.012	0.071
5)	0.003	0.028	0.005	0.063	0.061	0.021	0.005	0.016	0.012	0.026	0.068
6)	0.081	0.101	0.100	0.135	0.090	0.268	0.244	0.101	0.213	0.201	0.130
7)	0.008	0.032	0.009	0.040	0.008	0.030	0.208	0.010	0.027	0.021	0.067
8)	0.007	0.027	0.006	0.050	0.025	0.019	0.063	0.296	0.012	0.021	0.064
9)	0.018	0.047	0.030	0.051	0.061	0.195	0.046	0.114	0.149	0.046	0.093
10)	0.007	0.032	0.010	0.099	0.015	0.047	0.015	0.021	0.032	0.094	0.072

Notes: This table reports the share of total intermediates used by the consuming sector that comes from the producing sector. (For example, 12.6% of the total intermediates used by the third sector stem from the second sector in Europe.) The shares were computed by the authors based on the World Input-Output Database for the year 2014.

Table A.6: Calibration of environmental parameters

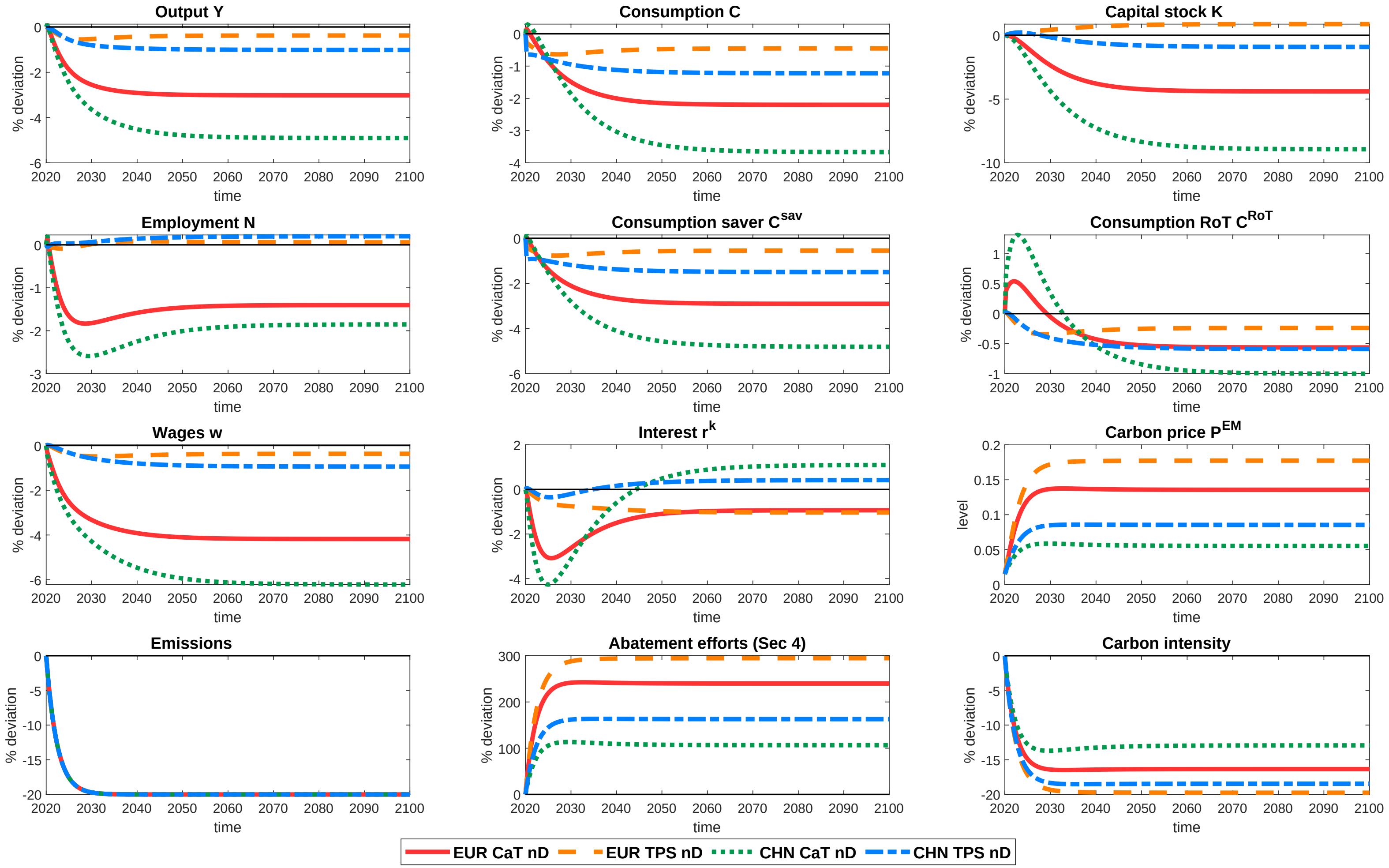
Variable/Parameter	Symbol	Value
Pollution decay	$1-\rho^{EM}$	0.9979
Abatement cost parameter (proportional)	ϕ_1	0.185
Abatement cost parameter (potent)	ϕ_2	2.8
Damage parameter (constant)	$\gamma_{0,EU28}$	$\gamma_{0,CHN}$
	0.4098	0.4098
Damage parameter (proportional)	$\gamma_{1,EU28}$	$\gamma_{1,CHN}$
	-0.0070	-0.0020
Damage parameter (quadratic)	$\gamma_{2,EU28}$	$\gamma_{2,CHN}$
	3.1076e-05	2.4481e-06
Carbon intensity:	$(1-\bar{U}_s)\bar{\kappa}_s$	
	EU28	CHN
1) Agriculture, forestry and fishing	0.157	0.112
2) Manufacturing (Non-ETS)	0.331	0.912
3) Manufacturing (NETS)	0.021	0.050
4) Water supply	0.101	0.727
5) Construction	0.024	0.024
6) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.053	0.061
7) Transport (ETS)	0.699	0.610
8) IT and communication	0.006	0.005
9) Prof., scient. and techn. & admin. and support services	0.011	0.036
10) Arts, entertainment, recreation & oth. services	0.018	0.123
11) Energy	0.730	1.467

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: No emissions damage

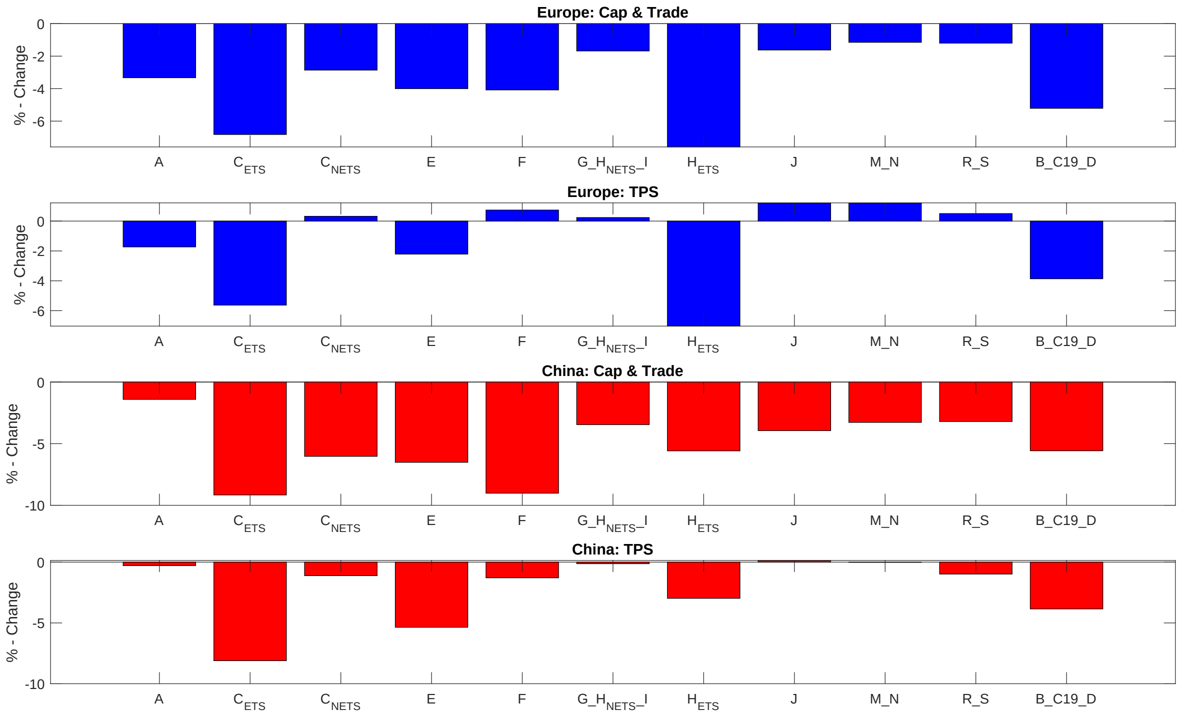
In this appendix, we show the simulation results when neglecting economic damage from emissions, i.e. $\gamma_0 = \gamma_1 = \gamma_2 = 0$.

Figure B.1: Implications for selected macroeconomic and environmental variables without emissions damage



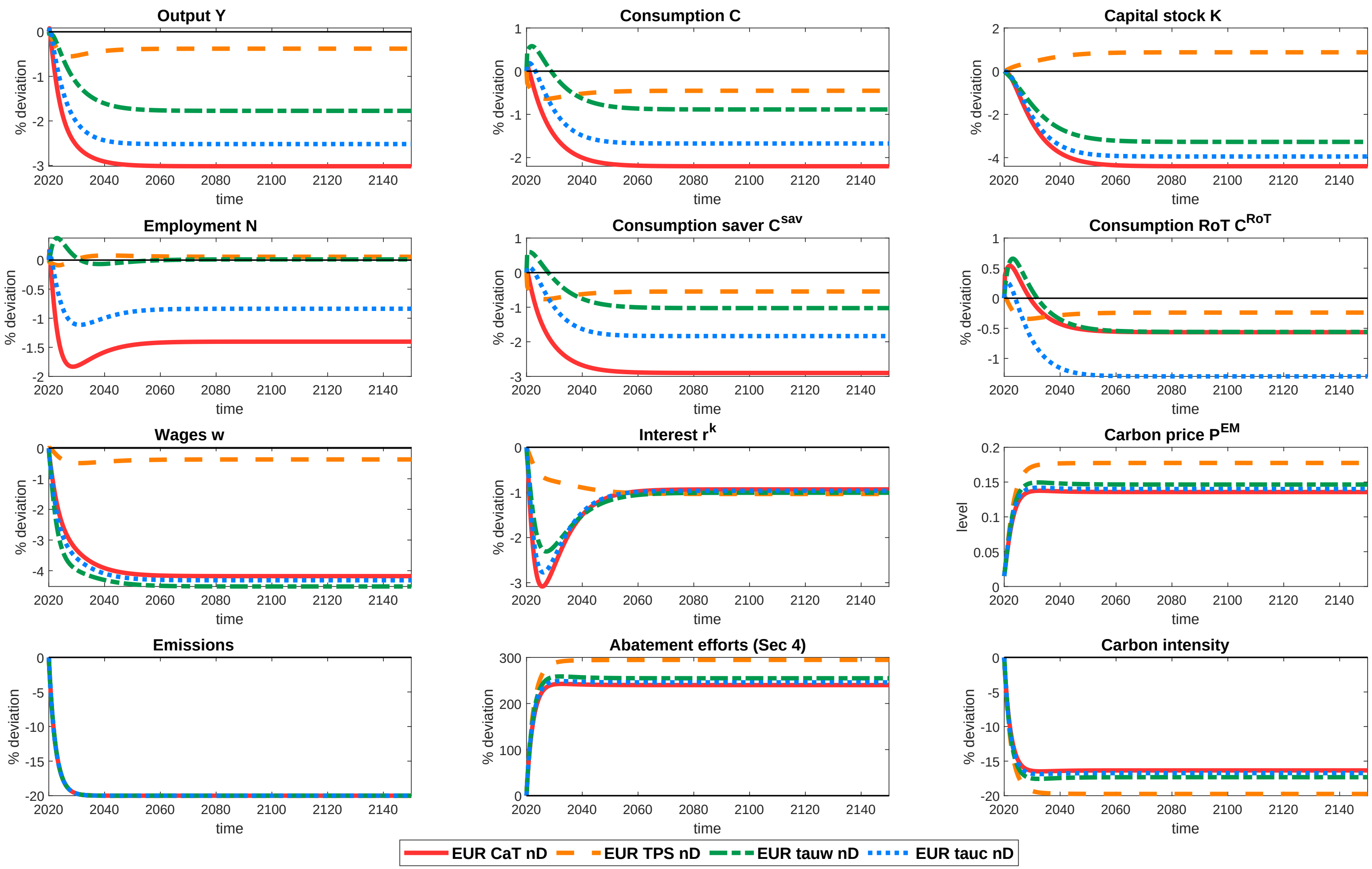
Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under CaT and TPS in Europe (red and orange) and China (green and blue) when neglecting economic emissions damage. Depicted is the transition until 2100.

Figure B.2: Implications for long-run sectoral output without emissions damage



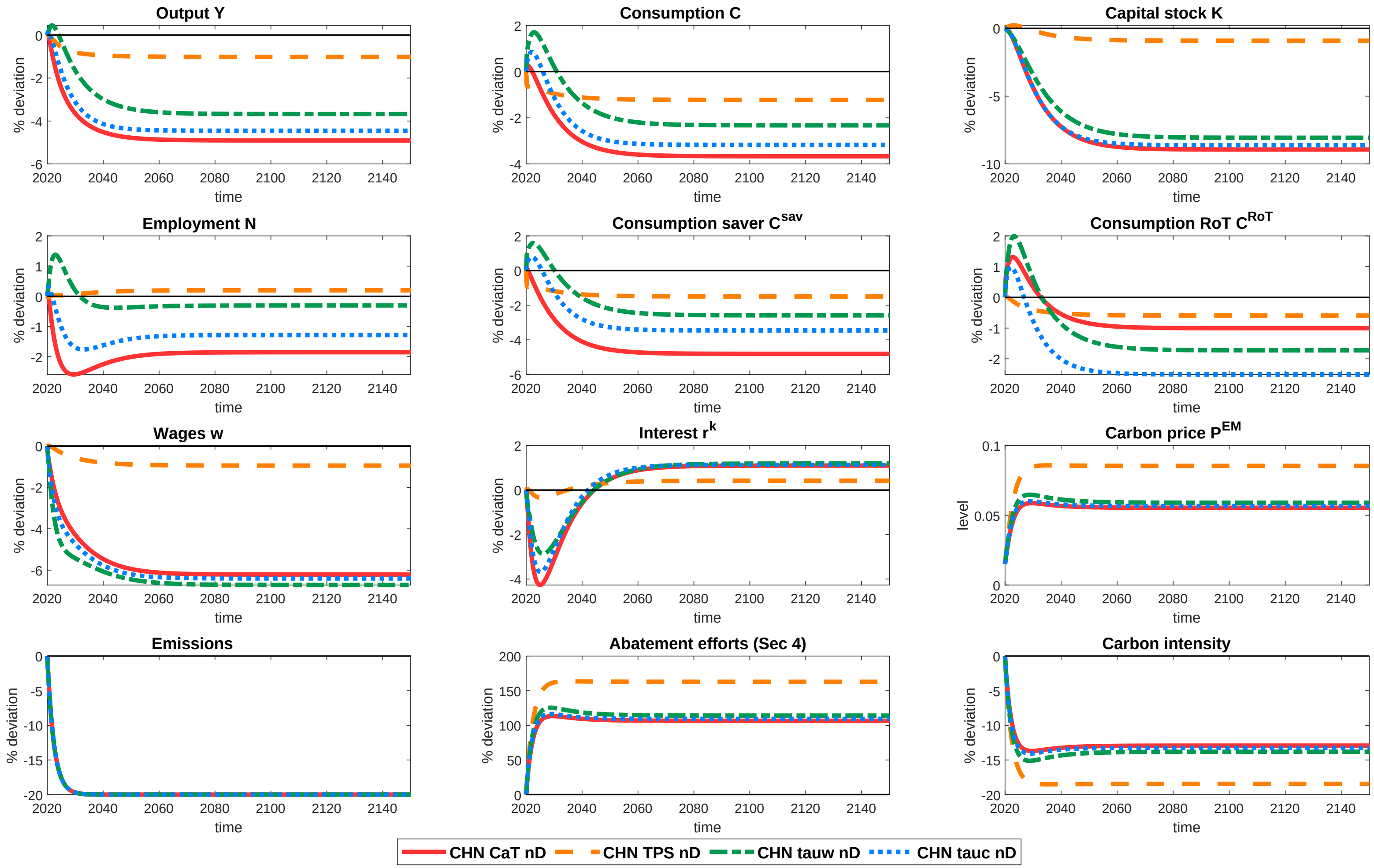
Notes: Figure shows the effects of an emissions reduction of 20% on sectoral value added under CaT and TPS in Europe (blue) and China (red) when neglecting economic emissions damage.

Figure B.3: Implications for selected macroeconomic and environmental variables when reducing taxes (Europe) without emissions damage



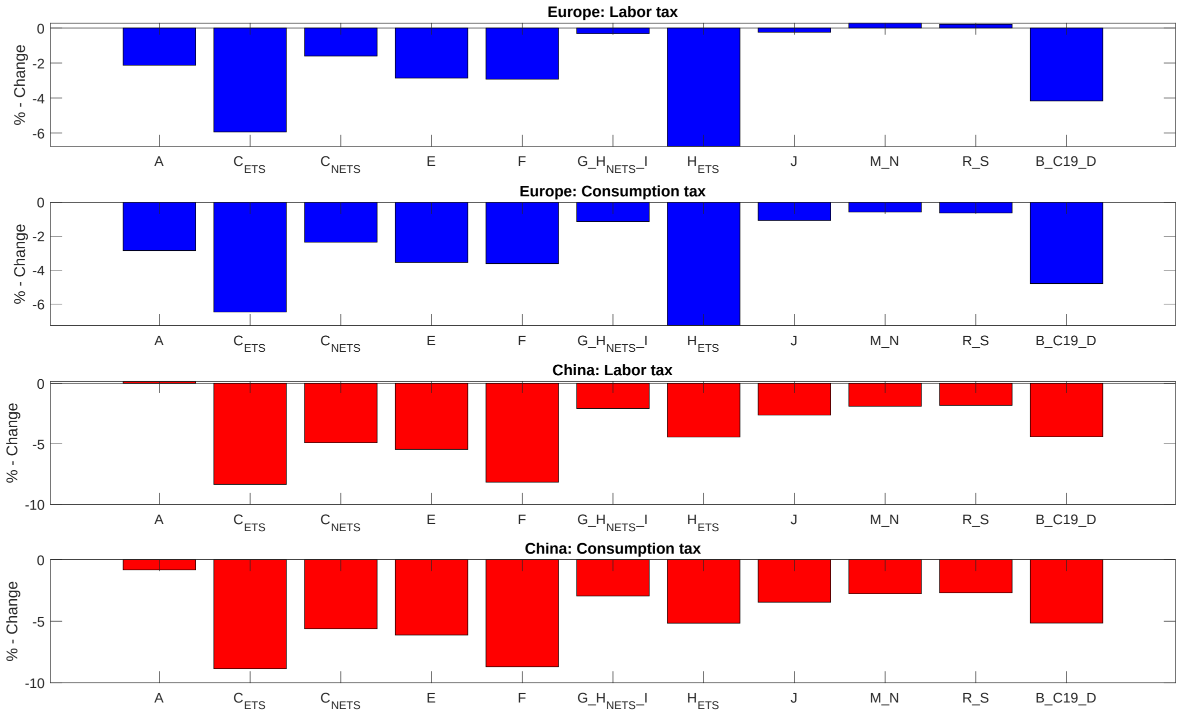
Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under CaT and combined with tax reductions in Europe when neglecting economic emissions damage.

Figure B.4: Implications for selected macroeconomic and environmental variables when reducing taxes (China) without emissions damage



Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under CaT and combined with tax reductions in China when neglecting economic emissions damage.

Figure B.5: Implications of CaT with tax reductions for long-run sectoral output without emissions damage

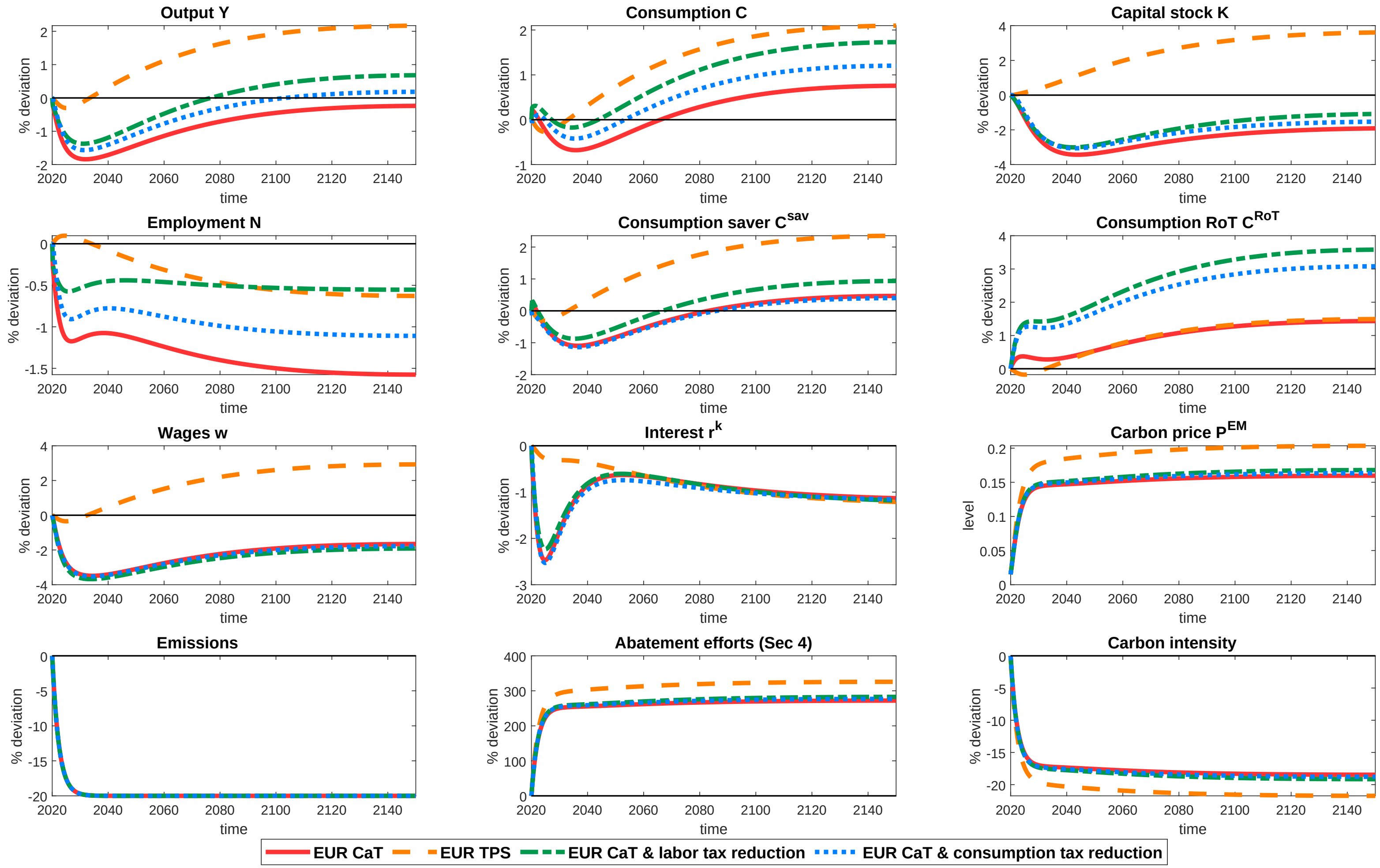


Notes: Figure shows the effects of an emissions reduction of 20% on sectoral value added under CaT and tax reductions when neglecting economic emissions damage.

Appendix C: Alternative utility function and no distortionary tax rates

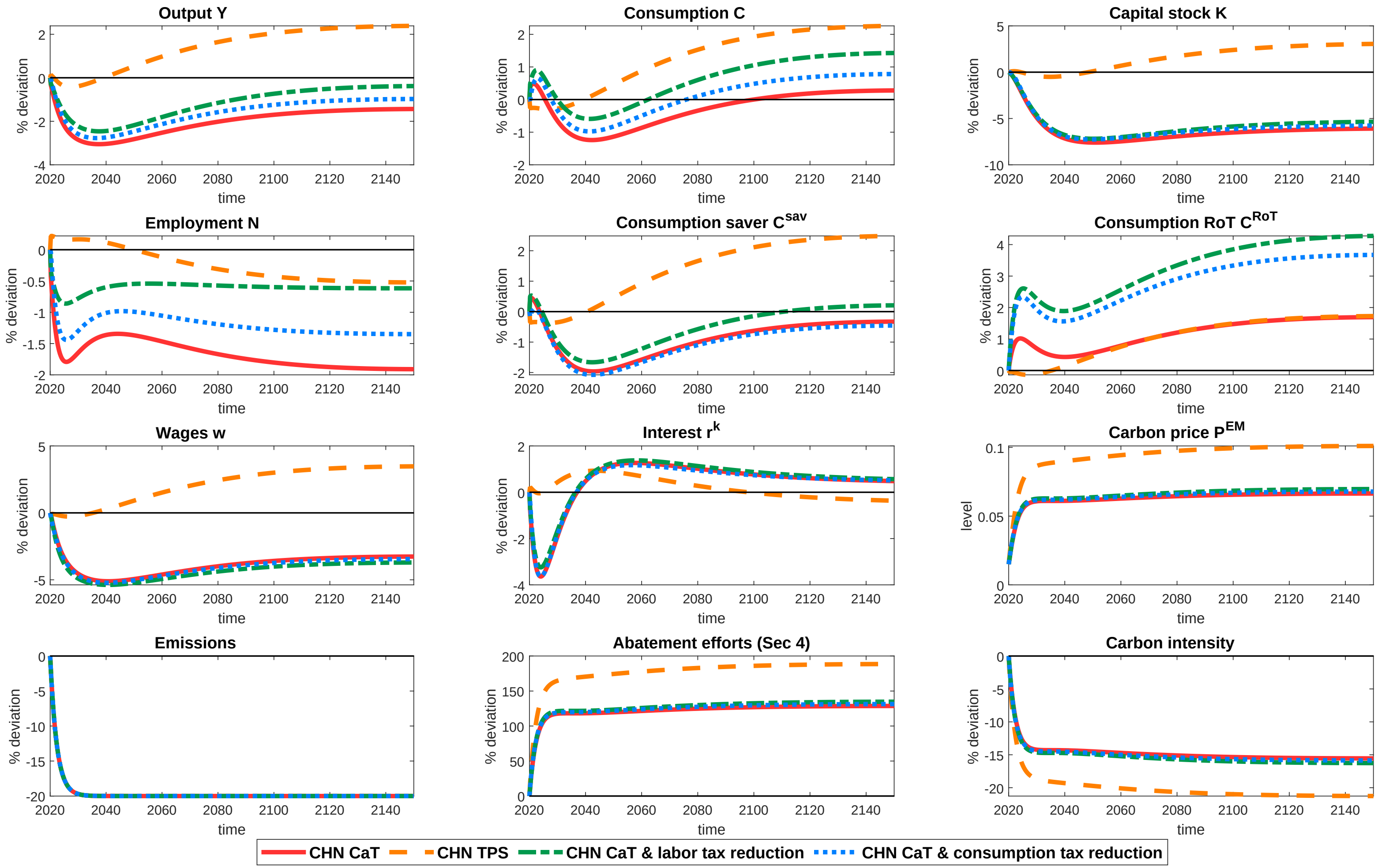
In this appendix, we show the simulation results when using an additively separable utility function (Fig. C.1- Table C.1), setting initial labor and consumption tax rates to zero (Figure C.3- Table C.2) or both (Fig. C.4- Table C.3) .

Figure C.1: Implications for selected macroeconomic and environmental variables when using an additively separable utility function (Europe)



Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under TPS, CaT and combined with tax reductions in Europe when using an additively separable utility function

Figure C.2: Implications for selected macroeconomic and environmental variables when using an additively separable utility function (China)



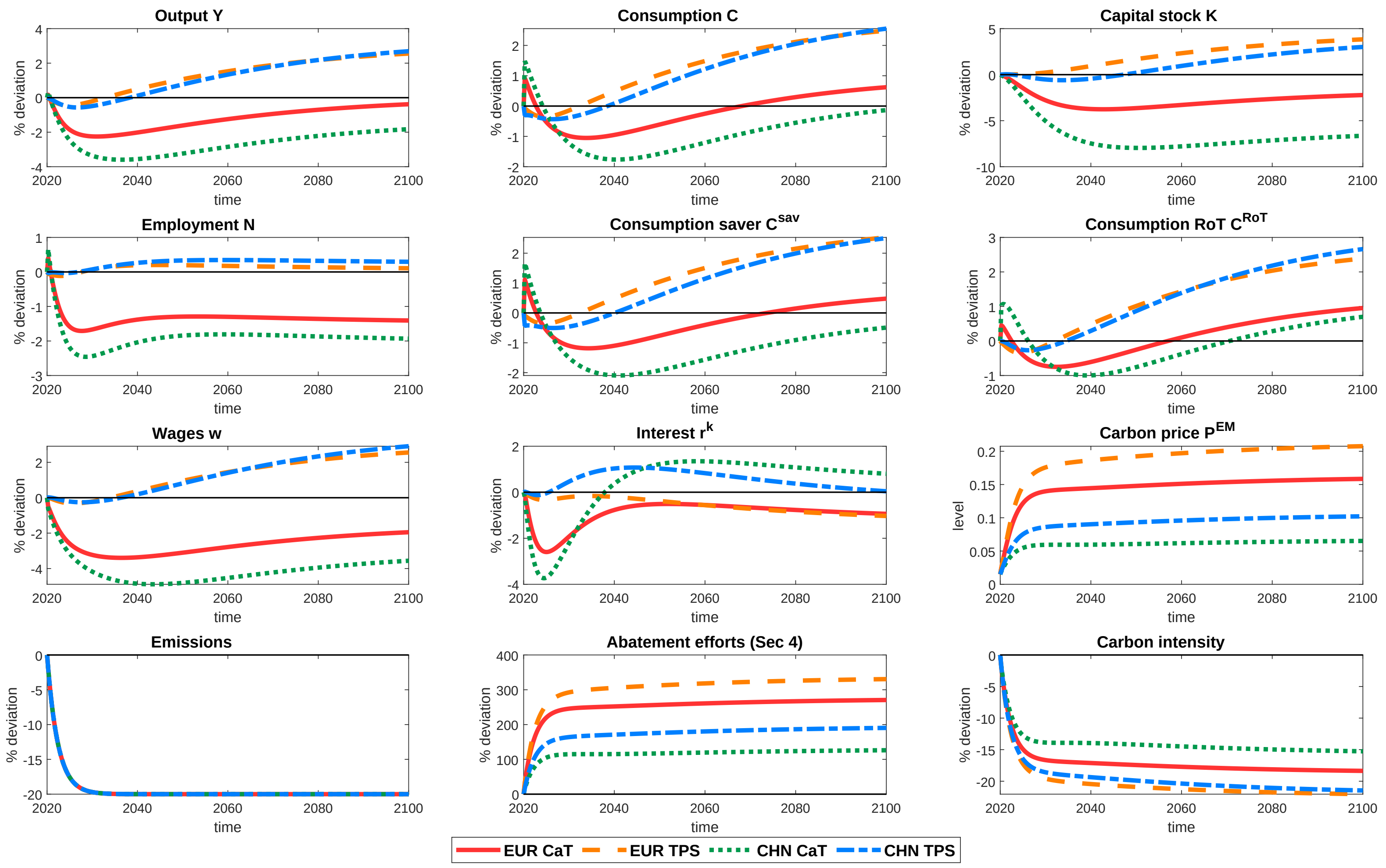
Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under TPS, CaT and combined with tax reductions in China when using an additively separable utility function.

Table C.1: Welfare effects of TPS, CaT and tax reductions with an additively separable utility function

	Optimizers	RoTs	Aggregate
With transition...			
EUR CaT	-0.11	1.57	0.39
EUR TPS	0.76	0.43	0.66
EUR $\tau^w \downarrow$	-0.37	2.95	0.63
EUR $\tau^c \downarrow$	-0.51	2.90	0.51
CHN CaT	-0.67	2.23	0.20
CHN TPS	0.44	0.42	0.44
CHN $\tau^w \downarrow$	-0.99	3.95	0.49
CHN $\tau^c \downarrow$	-1.17	3.87	0.34

Notes: Table shows welfare implications of different carbon pricing regimes assuming an additively separable utility function. Welfare is expressed as consumption-equivalent gain for the respective household in line with Lucas (2003), in percentage deviations from initial steady state. The aggregate welfare effects are a population size-weighted average.

Figure C.3: Implications for selected macroeconomic and environmental variables without labor and consumption taxes



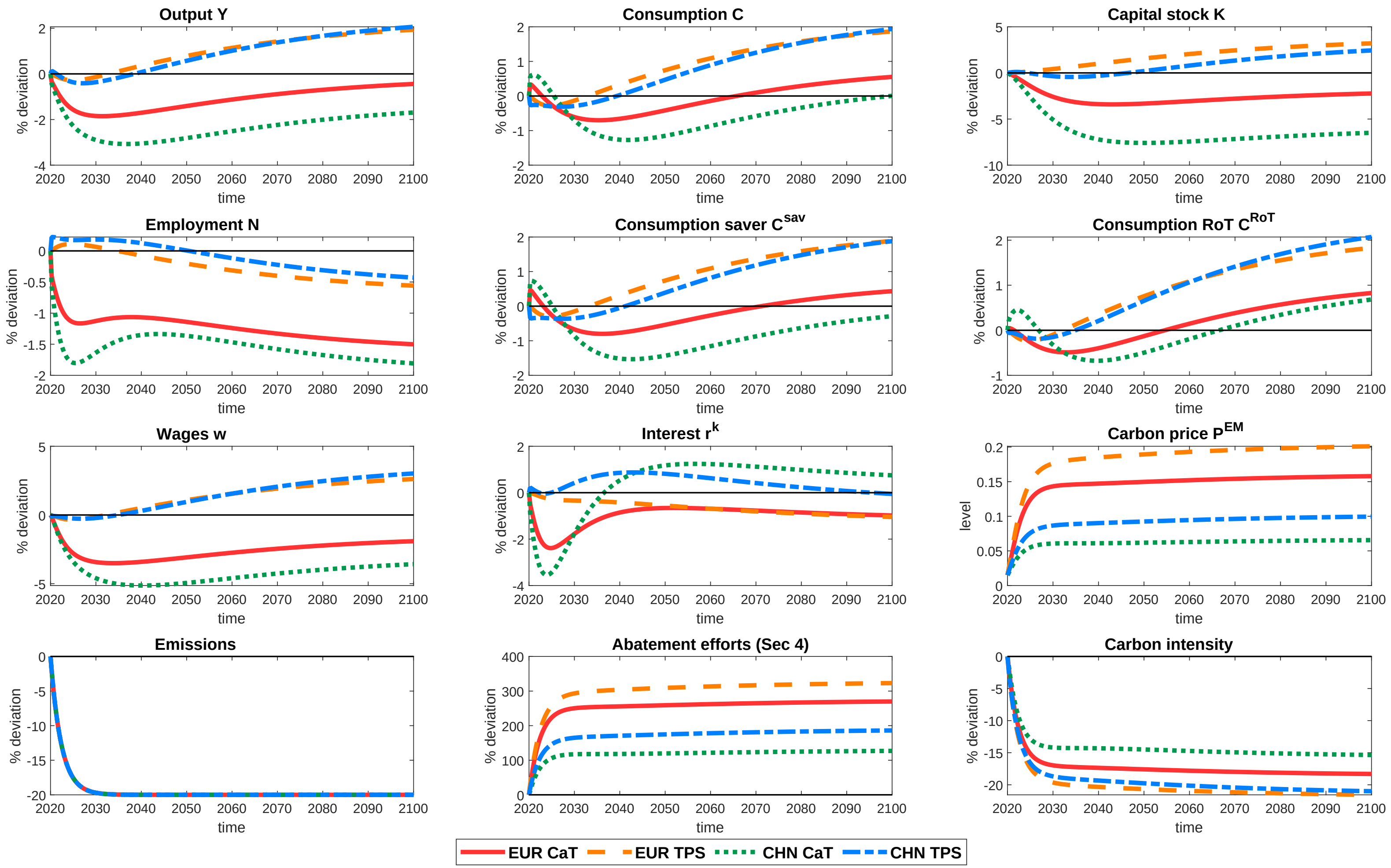
Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under CaT and TPS in Europe (red and orange) and China (green and blue) when setting distortionary labor and consumption taxes to zero in initial steady state. Depicted is the transition until 2100.

Table C.2: Welfare effects without labor and consumption taxes

	Optimizers	RoTs	Aggregate
With transition...			
EUR CaT	0.48	0.82	0.58
EUR TPS	0.52	0.49	0.51
CHN CaT	0.25	1.17	0.53
CHN TPS	0.23	0.49	0.31

Notes: Table shows welfare implications of different carbon pricing regimes assuming zero distortionary labor and consumption taxes in initial steady state. Welfare is expressed as consumption-equivalent gain for the respective household in line with Lucas (2003), in percentage deviations from initial steady state. The aggregate welfare effects are a population size-weighted average.

Figure C.4: Implications for selected macroeconomic and environmental variables with additively separable utility function and without labor and consumption taxes



Notes: Figure shows the effects of an emissions reduction of 20% on macroeconomic and environmental variables under CaT and TPS in Europe (red and orange) and China (green and blue) when assuming an additively separable utility function and setting distortionary labor and consumption taxes to zero in initial steady state. Depicted is the transition until 2100.

Table C.3: Welfare effects with additively separable utility function and without labor and consumption taxes

	Optimizers	RoTs	Aggregate
With transition...			
EUR CaT	0.66	1.15	0.81
EUR TPS	0.71	0.74	0.72
CHN CaT	0.35	1.58	0.72
CHN TPS	0.31	0.73	0.44

Notes: Table shows welfare implications of different carbon pricing regimes assuming an additively separable utility function and zero distortionary labor and consumption taxes in initial steady state. Welfare is expressed as consumption-equivalent gain for the respective household in line with Lucas (2003), in percentage deviations from initial steady state. The aggregate welfare effects are a population size-weighted average.

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