DEUTSCHE
BUNDESBANK
EUROSYSTEM

Discussion Paper

Deutsche Bundesbank
No 50/2021

Using energy and emissions taxation to finance labor tax reductions in a multi-sector economy: An assessment with EMuSe

Natascha Hinterlang
Anika Martin
Oke Röhe
Nikolai Stähler
Johannes Strobel

Deutsche Bundesbank, Wilhelm-Epstein-Straße 14, 60431 Frankfurt am Main,
Postfach 10 06 02, 60006 Frankfurt am Main

Tel +49 69 9566-0

Please address all orders in writing to: Deutsche Bundesbank,
Press and Public Relations Division, at the above address or via fax +49 69 9566-3077

Internet http://www.bundesbank.de

ISBN 978–3–95729–860–7
ISSN 2749–2958

Non-technical summary

Research Question

Mitigating climate change by curbing carbon emissions is at the top of the political agenda in many countries across the world. To this end, policymakers worldwide have recently introduced or are in the process of introducing energy and/or emissions taxes. Budget-neutral labor tax reductions not only constitute a potential measure to alleviate the additional burden resulting from energy and/or emissions taxes, but are also at the center of political discourse in a range of euro area economies. Against this background, we analyze the effects of financing a labor tax reduction by higher energy or emissions taxes. We compare the resulting effects with those of using higher consumption taxes as a financing instrument, which are typically used in such an experiment.

Contribution

The implementation of such measures is not very likely to affect production across sectors or final demand in a homogenous way. Therefore, we build a dynamic stochastic general equilibrium model that features a detailed production network as well as environmental externalities in order to account for the heterogeneity regarding, for example, emission intensities and the interconnectedness of production through intermediate inputs such as energy.

Results

We find that implementing energy and/or emissions taxes as a financing instrument might outperform the use of consumption taxes typically used in such experiments if the economic damage from environmental pollution is sufficiently high. This is mainly driven by a positive "productivity-like" shock resulting from a tax-induced decrease in polluting activities. However, it takes time before the positive effects materialize. In addition, we show that individual sectors within the economy are affected differently. Manufacturing, transportation and energy production sectors tend to lose (or gain only a little) while administration, services and research sectors tend to benefit from using environmental taxation as a financing instrument.

Nichttechnische Zusammenfassung

Forschungsfrage

Die Eindämmung des Klimawandels durch eine Verringerung von Kohlendioxidemissionen steht in vielen Ländern der Welt oben auf der politischen Agenda. Zu diesem Zweck haben politische Entscheidungsträger weltweit die Besteuerung von Emissionen eingeführt oder sind dabei eine solche einzuführen. Budgetneutrale Senkungen der Lohneinkommensbelastung stellen in diesem Zusammenhang nicht nur eine potenzielle Maßnahme dar, um die zusätzliche Belastung durch Energie- und/oder Emissionssteuern zu verringern, sondern stehen in einer Reihe von Euro-Ländern bereits seit längerem im Zentrum wirtschaftspolitischer Diskussionen. Vor diesem Hintergrund werden in der vorliegenden Arbeit die Effekte einer durch Energie- oder Emissionssteuern finanzierten Reduktion der Lohneinkommensbelastung analysiert. Die Effekte dieser fiskalpolitischen Maßnahmen werden dabei mit denen verglichen, die bei einer typischerweise unterstellten Finanzierung der Lohneinkommensbelastung durch Verbrauchssteuern entstünden.

Beitrag

Es ist unwahrscheinlich, dass die oben angeführten (klima)politischen Maßnahmen die Produktion in verschiedenen Wirtschaftszweigen oder die Nachfrage nach einzelnen Gütern in gleicher Weise beeinflussen. Folglich wird ein dynamisches stochastisches allgemeines Gleichgewichtsmodell mit einem detaillierten Produktionsnetzwerk sowie Umweltexternalitäten verwendet, um etwa der Heterogenität in Bezug auf Emissionsintensitäten oder Produktionsverflechtungen durch Vorleistungen (wie beispielsweise Energie) angemessen Rechnung zu tragen.

Ergebnisse

Die Untersuchung zeigt, dass bei hinreichend hohen, produktionsbedingten Umweltschäden die Verwendung von Energie- und/oder Emissionssteuern als Finanzierungsinstrument vorteilhafter sein kann als der Einsatz von Verbrauchersteuern. Dies ist im Wesentlichen auf einen „produktivitätsfördernden" Effekt zurückzuführen, der durch eine Abschwächung des Umweltschadens entsteht. Es dauert jedoch eine gewisse Zeit, bis sich dieser Effekt materialisiert, das heißt, bis sichtbar wird, dass Energie und/oder Emissionsbesteuerung einem Einsatz von Verbrauchssteuern überlegen ist. Darüber hinaus zeigen wir, dass einzelne Wirtschaftssektoren unterschiedlich stark durch die fiskalischen Maßnahmen betroffen sind. So werden energieintensive Sektoren, wie das produzierende Gewerbe, der Transportsektor oder die Energieerzeugung, stärker von einer Umweltsteuer als Finanzierungsinstrument belastet als arbeitsintensive Sektoren, wie etwa die Verwaltung, der Dienstleistungssektor oder die Forschung.

Deutsche Bundesbank Discussion Paper No 50/2021

Using Energy and Emissions Taxation to Finance Labor Tax Reductions in a Multi-Sector Economy: An Assessment with EMuSe*

Natascha Hinterlang
Deutsche Bundesbank

Anika Martin
Deutsche Bundesbank

Oke Röhe
Deutsche Bundesbank

Nikolai Stähler
Deutsche Bundesbank

Johannes Strobel
Deutsche Bundesbank

Abstract

In this paper, we introduce a closed-economy version of the dynamic **e**nvironmental **mu**lti-**se**ctor general equilibrium model *EMuSe* to analyze the effects of financing a labor tax reduction through higher consumption, energy or emissions taxation. We find that, for sufficiently high environmental damage, using energy and emission taxes as the financing instrument eventually outperforms the use of consumption taxes due to a positive productivity-like shock. However, it takes time for the positive effects to materialize. Manufacturing, transportation and energy production sectors tend to lose (or gain only a little) while administration, services and research sectors tend to benefit from the implementation of an environmental taxation as a financing instrument. As demand shifts towards sectors less affected by the tax shift, the aggregate economic effects are different in the multi-sector economy compared to a conventional one-sector-economy framework.

Keywords: EMuSe, Dynamic General Equilibrium Model, Sectoral Heterogeneity, Environmental Tax Policy, Input-Output Matrix

JEL classification: E32, E50, E62, H32, Q58

---

*Contact address: Deutsche Bundesbank, Wilhelm-Epstein-Strasse 14, 60431 Frankfurt, Germany. E-mail: natascha.hinterlang@bundesbank.de, anika.martin@bundesbank.de, oke.roehe@bundesbank.de, nikolai.staehler@bundesbank.de, johannes.strobel@bundesbank.de. The paper represents the authors' personal opinions and does not necessarily reflect the views of the Deutsche Bundesbank or the Eurosystem. Any errors are ours. We would like to thank Hafedh Bouakez, Samuel Hurtado, Maria Longson, Christoph Schult, Igor Vetlov, Henning Weber, members of the Bundesbank's DSGE group and of the European System of Central Banks' Working Group on Econometric Modelling (WGEM) as well as participants of the 23rd INFER conference 2021 and of the 22nd IWH-CIREQ-GW Macroeconometric Workshop on Environmental Macroeconomics for their helpful comments.

1 Introduction

Mitigating climate change by curbing anthropogenic carbon emissions is at the top of the political agenda in many countries across the globe. To this end, policymakers worldwide have recently introduced or are in the process of introducing energy and/or emission taxes. However, the implementation of such measures is not very likely to affect production across sectors or final demand in a homogenous way, given heterogeneity regarding emission intensities or the interconnectedness of production through intermediate inputs. As budget-neutral labor tax reductions not only constitute a potential measure to alleviate the additional burden resulting from energy and/or emissions taxes but also rank high on the political agenda in a range of euro area economies (see European Commission, 2013, 2014, 2015, 2016; IMF, 2014; or OECD, 2012, 2015), it is a natural experiment to use the proceeds of an energy and/or emissions tax to finance such a reduction.

Against this background, this paper shows that implementing energy and/or emissions taxes as a financing instrument might outperform the use of consumption taxes typically used in such experiments if the economic damage from environmental pollution is sufficiently high. This is mainly driven by a positive "productivity-like" shock resulting from a tax-induced decrease in polluting activities. We thus contribute to the existing literature which suggests that shifting the tax burden away from labor towards less distortive and potentially externality-mitigating taxation benefits economic performance and welfare while, at the same time, curbing pollution (see OECD, 2019, 2021; IMF, 2020; and European Commission, 2019). In addition, we show that individual sectors within the economy are affected differently. While administration, services and research sectors tend to benefit from using environmental taxation as a financing instrument in terms of output, manufacturing, transportation and energy production sectors tend to lose (or gain only a little).

Our modelling framework is a closed-economy version of *EMuSe*, an environmental dynamic stochastic general equilibrium (E-DSGE) model featuring multiple interrelated production sectors that vary in their emissions intensity, factor intensity, use of intermediate inputs, and contribution to final demand. Emissions occur as a by-product of production and differ by sector, while the price per unit of emission is the same across sectors. 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. Goods sold by different sectors may be taxed differently. Overall, the model not only takes into account the heterogeneous effects associated with environmental policy measures; by capturing sectoral linkages, we can also assess the impact on key macroeconomic and environmental aggregates such as value added, welfare, emissions, carbon concentration as well as associated damages across sectors. We specify a version of *EMuSe*, which is calibrated to 54 sectors relying on the standard NACE Rev. 2 classification using the most recent release of the World Input-Output Database (WIOD). Regarding the environmental module, we rely on the environmental accounts provided by the European Commission, which are consistent with the WIOD (see Corsatea, Lindner, Arto, Roman, Rueda-Cantuche, Afonso, Amores, Neuwahl, et al., 2019). The model is parameterized to depict EU27 countries plus the UK.

Our results can be summarized as follows. A reduction in labor income taxation reduces labor costs and thereby fosters production and employment. Higher aggregate net income stimulates demand. Using a general consumption tax as a financing instrument leads to a policy-induced increase in consumption costs and thereby reduces the positive effects of the labor tax reduction. The stimulating effect still dominates, however, because a higher consumption tax rate generates relatively few distortions on the demand side (compared to a tax on specific consumption goods, such as energy) and avoids distortions on the production side (relative to taxes on production inputs). However, this tax shift comes at the cost of higher emissions as production increases without raising incentives for firms to reduce pollution. If the economic damage from emissions is high enough, the use of energy and/or emissions taxes to finance the labor tax reduction might therefore outperform the use of consumption taxes in terms of both economic performance and welfare. It can take 30 years or more before the positive effects materialize (depending on the financing instrument chosen, the impact on emissions and the calibration of the damage function).

What is the mechanism behind this finding? When ignoring the economic damage of emissions, energy and emissions taxation distorts factor and/or consumption demand in an unfavorable way such that output falls. With a conventional Walrasian labor market, as in the *EMuSe* model, the distortions caused by labor taxation are smaller than the ones caused by energy and emissions taxation (in most sectors). When taking into account the environmental damage, however, these taxes address an externality by pricing pollution and reducing emissions. A lower emission stock eventually boosts (sectoral and aggregate) productivity and thereby output and income. In other words, a lower emission stock is akin to a positive, permanent productivity shock and, eventually, the associated benefits outweigh the relatively larger tax distortions. As one would expect, energy/emissions taxation affects emissions-intensive sectors and those that need these products as inputs (such as manufacturing and transportation) more than sectors that cause fewer emissions and need less emissions-intensive intermediate goods (such as administration, services, IT and research). In this context, it should be noted that the macroeconomic effects in the multi-sector economy differ from those in a conventional one-sector economy because of the inter-sectoral linkages. In *EMuSe*, the sectors that are more affected by an increase in emissions costs must raise their prices more. Consequently, demand shifts to sectors that are less affected and/or even benefit disproportionately from the payroll tax cut. In contrast, in a one-sector economy where producers use part of their own output as intermediate inputs, the negative economic effects of emissions pricing are larger because intermediate input costs rise sharply and there are no substitution possibilities.[1]

Moreover, we find that, in the presence of a sufficiently large economic damage of the pollution stock, the emissions reduction after an increase in energy and/or emissions taxation is slightly smaller than it is in a situation with low or no damage. This is a result of the “productivity boost”-induced positive output and consumption effect just described. Even though emissions per unit produced fall (also due to more abatement), overall emissions decrease less because demand and production increase more. Hence, economic growth and emission reduction are realized simultaneously but the decline in aggregate emissions is smaller in the presence of higher economic growth.

When taking into account pollution damage, a tax on emissions turns out to be most

[1] Simulations comparing the results of a one-sector economy with those of our multi-sector economy have been relegated to the appendix to save space. There, we also discuss the role of roundabout production.

beneficial in terms of output and consumption gains in the new steady state. In this case, emission reduction is largest, which generates the highest "productivity boost". The introduction of emissions taxes, however, generates a relatively large downturn on impact, and it takes roughly 30 years before the positive effects become prevalent. In terms of welfare, the use of final energy consumption taxation as a financing instrument turns out to be most beneficial in our simulations. It generates relatively small distortions on the production side and a sufficient reduction in demand for energy, which is emission-intensive in production. The negative effects, also on impact, are basically limited to the energy sectors, while the other sectors tend to gain. Furthermore, it is the second-best instrument when ignoring economic damage. Our analysis therefore suggests that using final energy consumption to finance a labor tax reduction seems to be a good idea.

An important caveat to our analysis is that distributional aspects are not considered. The household sector only consists of a representative optimizing household. Low-income households or those who depend on transfers but need to purchase energy may actually lose (given that the energy tax rate increases by roughly 25 percentage points in our simulations). Distributional issues may also play a role if we take into account that relatively more poor households tend to work in emissions and energy-intensive sectors (for example, mining, transportation, manufacturing), while wealthier households tend to be engaged in sectors that cause fewer emissions (such as administration, services and information technology). Since the former sectors lose from emissions taxation while the latter benefit, the aggregate welfare gain will crucially depend on the wealth/income distribution of households. These important aspects of environmental policies certainly need to be assessed in future research. This, however, is beyond the scope of the present paper.

The rest of the paper is organized as follows. We discuss related literature in Section 2. The model is introduced in Section 3, its calibration in Section 4. The simulations are described in Section 5, and Section 6 concludes.

2 Related literature

Our paper is related to several strands of the literature. First, it relates to the literature discussing a shift away from labor towards consumption taxation, often referred to as "fiscal devaluation".[2] Second, it relates to the literature using multi-sector models. Finally, our study is linked to the literature discussing environmental issues in a DSGE framework.

Positive effects of a labor tax reduction financed by higher consumption taxation on output and welfare are found by Annicchiarico, Dio, and Felici (2015), Boscá, Doménech, and Ferri (2013), Burlon, Notarpietro, and Pisani (2021), Gadatsch, Stähler, and Weigert

[2]Strictly speaking, fiscal devaluation does not necessarily correspond to a permanent tax shift. Farhi, Gopinath, and Itskhoki (2014) provide a formal analysis of fiscal devaluations in a New Keynesian open economy DSGE model. They find that an intended nominal devaluation vis-a-vis a foreign economy can be robustly replicated with a small set of fiscal instruments: lower labor income financed by higher consumption taxes. Hence, fiscal devaluation is a sequence of taxes that replicates a sequence of nominal exchange rates while leaving the labor tax wedge constant (see also Kaufmann, 2019). However, also permanent tax shifts have frequently been termed "fiscal devaluation" in the literature. We adapt this convention.

(2016), Gomes, Jacquinot, and Pisani (2016), Lipińska and von Thadden (2019) and Stähler and Thomas (2012) in DSGE models calibrated to France, Germany, Italy, Portugal, Spain or the euro area. Engler, Ganelli, Tervala, and Voigts (2017) show that, when reducing labor taxes levied on employers, the beneficial effects may be increased, which – at least for the short run – is confirmed in an analysis by Burgert and Roeger (2014). Jacquinot, Lozej, and Pisani (2018) show that, if monetary policy is accommodative, positive effects are larger. Attinasi, Prammer, Stähler, Tasso, and van Parys (2019) compare the effects of a labor tax reduction financed by higher consumption taxes to those using other financing instruments, such as lower public purchases or public employment, while a shift towards property taxation is discussed in Mora-Sanguinetti and Rubio (2014), Stähler (2019) and Bielecki and Stähler (2020). All these studies find positive effects of such tax shifts. Ruppert, Schön, and Stähler (2021) discuss distributional consequences of such a tax shift in a framework with overlapping generations. They find that, at the time that the tax shift takes place, current retirees and those close to retirement do not benefit from the tax shift because policy-induced consumption costs increase too much. None of the papers mentioned above uses energy or emissions taxation as a financing instrument.

A multi-industry model with inter-sectoral linkages is presented by Atalay (2017) to analyze the importance of sectoral shocks to business cycle fluctuations. Baqaee and Farhi (2019) apply such a model to trade, Baqaee and Farhi (2020) to the Covid-19 crisis, Bouakez, Rachedi, and Santoro (2021) use it to assess the impact of inter-sectoral linkages on the government spending multiplier (which they find to increase), and Pasten, Schoenle, and Weber (2020) analyze the role of heterogenous price rigidities for responses of sectoral output and inflation to a monetary policy shock (see also Bouakez, Cardia, and Ruge-Murcia, 2014). Bouakez, Cardia, and Ruge-Murcia (2011) introduce durable goods into such a framework. We apply our multi-sector framework in an environmental and fiscal context as we believe that inter-sectoral spillovers are especially important when taxing only specific sectors (or emissions). While Devulder and Lisack (2020) use a (static) computable general equilibrium model for a similar purpose, we also trace the transition path from the initial to the final steady state after the policy change. Antosiewicz, Lewandowski, and Witajewski-Baltvilks (2016) use a smaller multi-sector model to compare the implications of taxing either the inputs or final consumption of energy, industry, construction and transportation sectors for emission reduction and economic performance. Wendner (2001) uses an OLG model in which emissions taxation partially finances the pension system. Our results are comparable to these studies, but we are able to disaggregate the sector-specific impact of such a reform in more detail, and we differentiate between taxing (energy-)goods and emissions (in all sectors).

In recent years, the integration of environmental aspects in macroeconomic models has been and is still advancing rapidly. Therefore, we only refer to the most closely related papers. We follow Heutel (2012) and Golosov, Hassler, Krusell, and Tsyvinski (2014) and assume that emissions are a by-product of production activities, which has become a common assumption in environmental dynamic macroeconomic models. Alternatively, one could assume that pollution is a production input that may be optimally determined (see Fischer and Springborn, 2011, Böhringer, Fischer, and Rosendahl, 2014, and Böhringer and Fischer, 2020, among others, for a discussion). Given the multiple interrelated production sectors in our model, a mix of both modelling assumptions applies to our setup. Although we assume that emissions are a by-product of production, firms choose intermediate inputs and may or may not avoid emissions-intensive products depending on their price. We also need to determine how emissions affect the economy. Chang, Chen, Shieh, and Lai (2009) and Angelopoulos, Economides, and Philippopoulos (2013), for example, assume that households' utility depends positively on the environmental quality by simply including the stock of pollution in the households' utility function. Assuming a negative feedback from emissions on the efficiency of production (through a so-called "damage function") is proposed by Heutel (2012), Golosov et al. (2014) and Khan, Metaxoglou, Knittel, and Papineau (2019), for example; Chang et al. (2009) discuss the implications of both approaches. Damage functions represent a typical feature of integrated assessment models (IAMs) that try to translate emissions into temperature changes and these, in turn, into economic losses (see Nordhaus, 2008). We follow the literature by specifying a reduced-form relationship in which the damage is caused by the stock of emissions - a common short-cut in economic modelling.[3] The impact of emissions taxation and emissions caps on the business cycle in a one-sector E-DSGE model is also discussed by Annicchiarico and Di Dio (2015). They find that fluctuations are dampened, especially by emission caps. Chan (2020) confirms this in a two-region economy and also finds that, when not cooperating, tax fluctuations should be higher in each region than under cooperation. Annicchiarico and Diluiso (2019) show in an international setup that trade spillovers are affected by the environmental regime put in place, which is also the case in Duan, Ji, Lu, and Wang (2021), and Annicchiarico, Correani, and Di Dio (2018) find in a model with oligopolistic firms that the market structure and markups charged by firms depend on the actual environmental tax regime. A comprehensive recent overview of analyses in E-DSGE models can be found in Annicchiarico, Carattini, Fischer, and Heutel (2021). None of the papers mentioned above uses a multi-sector setup, however, which restricts them to deriving aggregate macroeconomic implications only. By contrast, our approach not only allows us to assess different implications in each sector, but also to capture the effects due to the interrelated production structure.

3 The model

Time t is discrete and runs forever. The model economy comprises $\mathcal{S} = \{1, 2, .., S\}$ production sectors, perfectly competitive labor and capital agencies, consumption, investment, and intermediate goods retailers, a representative household, as well as a fiscal authority. The representative household receives income from providing labor and capital to labor and capital agencies that channel them to sectoral goods producers. Labor and capital are not perfectly mobile across sectors. Household income is used for consumption and investment in physical capital. Sectoral output is transformed into bundles of consumption, investment, and intermediate goods. This is accomplished by perfectly competitive retailers. Besides the purchase of intermediate input bundles, firms rent capital and labor from the labor and capital agencies. Producers are price setters and prices differ across sectors due to different markups.[4] There is also heterogeneity with respect to factor inten-

[3]More elaborate modelling approaches that first map the pollution level to the climate and then map climate changes to damages or welfare losses within the economic model can be found in Cai and Lontzek (2019) and Cai (2020), for example.

[4]While our benchmark results are based on a flexible price setup, we also investigate the role of price-setting frictions as in Calvo (1983) in a robustness analysis (found in the appendix).

sities. Production causes emissions, which may differ across sectors. Firms can invest in costly abatement technologies and may face sector-specific economic/production damage resulting from the stock of pollution. A fiscal authority runs a balanced budget by paying out lump-sum transfers and receiving income from labor income, consumption, energy and emissions taxation. In what follows, we will describe the economy in more formal detail.

3.1 Representative household

A representative household chooses consumption C_t, labor supply N_t and physical capital investments I_t in order to maximize expected utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \kappa_N \frac{N_t^{1+\psi}}{1+\psi} \right]. \tag{1}$$

The parameter σ denotes the inverse of the elasticity of intertemporal substitution for consumption, β is the discount rate. The inverse of the Frisch elasticity of labor supply is determined by ψ, κ_N is the relative weight of the disutility of labor. $\mathbb{E}_0$ is the expectations operator at $t = 0$. The choices of the representative household are subject to

$$(1 + \tau_t^c) P_t^C C_t + \tilde{P}_t^I I_t = (1 - \tau_t^w) W_t N_t + R_t^k K_{t-1} + P_t^C TR_t + P_t^C \Pi_t,$$

where P_t^C is the consumer price index (CPI), $\tilde{P}_t^I$ is the nominal price of a basket of investment goods, I_t is a basket of investment goods, W_t is the nominal wage rate and R_t^k is the nominal rental rate of capital K_t. The average tax rate on the consumption good is τ_t^c and the average labor tax rate τ_t^w. TR_t are lump-sum transfers received by the government and Π_t denotes aggregate firm profits. In CPI-deflated real terms we get

$$(1 + \tau_t^c) C_t + P_t^I I_t = (1 - \tau_t^w) w_t N_t + r_t^k K_{t-1} + TR_t + \Pi_t, \tag{2}$$

where $P_t^I = \tilde{P}_t^I / P_t^C$, $w_t = W_t / P_t^C$ and $r_t^k = R_t^k / P_t^C$. Capital accumulation is represented by the following law of motion

$$K_t = (1 - \delta) K_{t-1} + I_t, \tag{3}$$

with δ denoting the rate of depreciation. From the standard intratemporal first order conditions for consumption and labor it follows that $\lambda_t = C_t^{-\sigma}/(1 + \tau_t^c)$ and $\kappa_N N_t^{\psi} = \lambda_t (1 - \tau_t^w) w_t$. The optimal intertemporal savings decision is characterized by

$$1 = \beta \cdot \mathbb{E}_t \left\{ \frac{\lambda_{t+1}}{\lambda_t} \cdot \frac{r_{t+1}^k + (1 - \delta) P_{t+1}^I}{P_t^I} \right\}, \tag{4}$$

which depends on changes in the relative investment price P_t^I.

3.2 Consumption and investment-goods retailers

The representative household demands bundles of consumption and investment goods C_t and I_t, which are traded at prices P_t^C and P_t^I, respectively. The production technology of a perfectly competitive, representative retailer that bundles sector-level consumption goods of the S sectors, $C_{s,t}$, is given by

$$C_t = \left[\sum_{s=1}^{S} \psi_{C,s}^{1-\sigma_C} C_{s,t}^{\sigma_C}\right]^{\frac{1}{\sigma_C}}.$$

The parameters $\psi_{C,s}$ and σ_C determine the consumption utility value and the elasticity of substitution between sector-level consumption goods. The representative consumption-goods retailer's optimization problem in CPI-deflated real terms can be written as

$$\max_{C_{s,t}} (1+\tau_t^c)C_t - \sum_{s=1}^{S}(1+\tau_{s,t}^c+\tau_{s,t}^{Ec})P_{s,t}C_{s,t},$$

where $P_{s,t}$ is the CPI-deflated producer price of sectoral good $s \in \mathcal{S}$. $\tau_{s,t}^c$ is the general consumption tax rate levied on products produced in sector s (for example the VAT rate, which we assume to be equal across sectors for simplicity), and $\tau_{s,t}^{Ec}$ the corresponding energy tax rate for products of sector s (which we allow to be sector-specific in what follows). Taking into account the bundling technology, this leads to the following first-order condition:

$$C_{s,t} = \psi_{C,s}\left(\frac{(1+\tau_{s,t}^c+\tau_{s,t}^{Ec})P_{s,t}}{(1+\tau_t^c)}\right)^{\left(-\frac{1}{1-\sigma_C}\right)} C_t \quad \forall s \in \mathcal{S}. \tag{5}$$

Plugging this expression into the constant elasticity of substitution aggregator of consumption goods shows that P_t^C is equal to the weighted sectoral consumption good prices. We obtain the following relation:

$$(1+\tau_t^c)\cdot P_t^C = \left[\sum_{s=1}^{S}\psi_{C,s}\left((1+\tau_{s,t}^c+\tau_{s,t}^{Ec})P_{s,t}\right)^{-\frac{\sigma_C}{(1-\sigma_C)}}\right]^{-\frac{(1-\sigma_C)}{\sigma_C}}, \tag{6}$$

where the aggregate tax rate on consumption is determined by

$$(1+\tau_t^c) = \frac{\left[\sum_{s=1}^{S}\psi_{C,s}\left((1+\tau_{s,t}^c+\tau_{s,t}^{Ec})P_{s,t}\right)^{-\frac{\sigma_C}{(1-\sigma_C)}}\right]^{-\frac{(1-\sigma_C)}{\sigma_C}}}{\left[\sum_{s=1}^{S}\psi_{C,s}\left(P_{s,t}\right)^{-\frac{\sigma_C}{(1-\sigma_C)}}\right]^{-\frac{(1-\sigma_C)}{\sigma_C}}} \tag{7}$$

as in Blazquez, Galeotti, Manzano, Pierru, and Pradhan (2019) and Blazquez, Galeotti, Manzano, Pierru, and Pradhan (2021). We assume an analogous bundling technology for investment goods,

$$I_t = \left[\sum_{s=1}^{S}\psi_{I,s}^{1-\sigma_I} I_{s,t}^{\sigma_I}\right]^{\frac{1}{\sigma_I}}, \tag{8}$$

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 except that we assume that investment goods purchases are tax-exempt. The price index (relative to CPI) is thus given by

$$P_t^I = \left[\sum_{s=1}^{S} \psi_{I,s} (P_{s,t})^{-\frac{\sigma_I}{(1-\sigma_I)}} \right]^{-\frac{(1-\sigma_I)}{\sigma_I}} . \tag{9}$$

3.3 Labor and capital agencies

Labor is not perfectly mobile across sectors. However, a perfectly competitive, representative labor agency hires the total amount of labor, N_t, at the CPI-deflated real wage w_t and sells it to intermediate goods producers operating in S different sectors, such that

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

where $\omega_{N,s}$ is the weight attached to labor provided to sector $s \in \mathcal{S}$, and ν_N determines the elasticity of substitution of labor across sectors, capturing the degree of labor mobility. The labor agency's optimization problem can be written as

$$\max_{N_{s,t}} w_{s,t} N_{s,t} - w_t \cdot N_t ,$$

which leads to the following first-order condition characterizing the sector-specific demand for labor types

$$N_{s,t} = \omega_{N,s} \left(\frac{w_{s,t}}{w_t} \right)^{-\left(\frac{1}{1-\nu_N}\right)} N_t \quad \forall s \in \mathcal{S}. \tag{10}$$

After plugging this expression into the CES aggregator of labor goods, we obtain the aggregate wage index[5]

$$w_t = \left[\sum_{s=1}^{S} \omega_{N,s} w_{s,t}^{-\frac{\nu_N}{(1-\nu_N)}} \right]^{-\frac{(1-\nu_N)}{\nu_N}} . \tag{11}$$

An analogous proceeding for the capital agency yields

$$K_{s,t} = \omega_{K,s} \left(\frac{r_{s,t}^K}{r_t^K} \right)^{-\left(\frac{1}{1-\nu_K}\right)} K_t \quad \forall s \in \mathcal{S}, \tag{12}$$

and

$$r_t^K = \left[\sum_{s=1}^{S} \omega_{K,s} (r_{s,t}^K)^{-\frac{\nu_K}{(1-\nu_K)}} \right]^{-\frac{(1-\nu_K)}{\nu_K}} . \tag{13}$$

[5] Note that we do not differentiate between labor taxation in different sectors (and also ignore progressive taxation).

3.4 Production

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

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

subject to

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

The parameter $\theta_s^P > 1$ governs the elasticity of substitution between different varieties and may differ across sectors. The standard first order conditions yield variety demand as

$$y_{s,t(z)} = \left[\frac{P_{s,t}(z)}{P_{s,t}}\right]^{-\theta_s^P} Y_{s,t}, \tag{14}$$

and the (CPI-deflated) producer price of the sectoral bundle as

$$P_{s,t} = \left[\int_0^1 P_{s,t}(z)^{1-\theta_s^P}\ dz\right]^{\frac{1}{1-\theta_s^P}} \qquad \forall s \in \mathcal{S}. \tag{15}$$

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

$$y_{s,t}(z) \leq [1 - D_s(M_t)]\, \varepsilon_{s,t} \left(K_{s,t-1}(z)^{1-\alpha_{N,s}} N_{s,t}(z)^{\alpha_{N,s}}\right)^{\alpha_{H,s}} (H_{s,t}(z))^{1-\alpha_{H,s}}, \tag{16}$$

where ε_s is total factor productivity, the α's determine factor intensity and $D_s(M_t)$ is a sector-specific damage function that positively depends on the emission stock M_t. We assume that emission-induced damage is either zero (in our first benchmark simulation) or we follow Heutel (2012) and assume that it is given by $D_s(M_t) = \gamma_{0,s} + \gamma_{1,s} \cdot M_t + \gamma_{2,s} \cdot M_t^2$. Following Annicchiarico and Di Dio (2015), emissions are a by-product of production, taking the form $Z_{s,t} = \kappa_s \cdot (1 - U_{s,t}) \cdot y_{s,t}$, where $\kappa_s \in [0, \infty)$ and $U_{s,t} \in [0,1)$ is costly abatement with an abatement cost function $C(U_{s,t}) = \phi_{1,s} \cdot U_{s,t}^{\phi_{2,s}} \cdot y_{s,t}$, where $\phi_{1,s} > 0$ and $\phi_{2,s} > 1$ (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 the index z to be dropped), we get the standard first-order conditions for labor, capital and intermediate inputs:

$$\begin{aligned} w_{s,t} &= \alpha_{H,s} \cdot \alpha_{N,s} \cdot mc_{s,t} \cdot \frac{y_{s,t}}{N_{s,t}}, && (17) \\ r^k_{s,t} &= \alpha_{H,s} \cdot (1-\alpha_{N,s}) \cdot mc_{s,t} \cdot \frac{y_{s,t}}{K_{s,t-1}}, && (18) \\ (1+\tau^{EH}_{s,t})P^H_{s,t} &= (1-\alpha_{H,s}) \cdot mc_{s,t} \cdot \frac{y_{s,t}}{Hs,t}, && (19) \end{aligned}$$

where $\tau^{EH}_{s,t}$ is the average tax rate on intermediate inputs in sector s and $P^H_{s,t}$ the CPI-deflated real price of these inputs. $mc_{s,t}$ are real marginal production costs in each sector. If emissions are priced at a price P^{em}_t, abatement is determined by

$$\phi_{1,s} \cdot \phi_{2,s} \cdot U^{\phi_{2,s}-1}_{s,t} = P^{em}_t \cdot \kappa_s. \tag{20}$$

For $P^{em}_t = 0$, 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 perspective. Firms are price setters and charge a markup on their marginal production costs. Under flexible prices, it holds that[6]

$$P_{s,t} = \tfrac{\theta^P_s - 1}{\theta^P_s} \cdot \tilde{mc}_{s,t}, \tag{21}$$

which is the standard pricing equation with markups, with one exception. For factor demand, the relevant marginal costs are $mc_{s,t}$, whereas they are

$$\tilde{mc}_{s,t} = mc_{s,t} + \phi_{1,s} \cdot U^{\phi_{2,s}}_{s,t} + P^{em}_t \cdot \kappa_s \cdot (1 - U_{s,t}) \tag{22}$$

in the pricing equation. Marginal costs relevant for pricing also include abatement costs and emissions taxes. They only equal marginal factor input costs whenever the price per emission is zero (and, thus, firms ignore these "extra costs"; see Annicchiarico and Di Dio, 2015, for details).

What remains to be determined is factor demand for sector j-intermediates by sector s, with $j, s \in \mathcal{S}$. Similar to the consumption and investment goods bundles, we assume that intermediates are bundled according to

$$H_{s,t} = \left[\sum_{j=1}^{S} \psi_{H,s,j}^{1-\sigma_{H,s}} H_{s,j,t}^{\sigma_{H,s}} \right]^{\frac{1}{\sigma_{H,s}}} \qquad \forall s \in \mathcal{S}.$$

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 $\psi_{H,s,j}$ and taking into account the elasticity of substitution between those intermediate goods, which is determined by $\sigma_{H,s}$. These parameters may differ across sectors. The optimization problem can thus be written as

$$\max_{H_{s,j,t}} P^H_{s,t}(1+\tau^{EH}_{s,t})H_{s,t} - \sum_{j=1}^{S}(1+\tau^{Ep}_{j,t})P_{j,t}H_{s,j,t} \quad \forall s \in \mathcal{S},$$

where $\tau^{Ep}_{s,t}$ is the energy tax rate. Proceeding analogously as we did for the consumption

[6] An extension with staggered prices is presented in the appendix.

bundle, we get

$$H_{s,j,t} = \psi_{H,s,j} \left(\frac{(1+\tau^{Ep}_{j,t})P_{j,t}}{(1+\tau^{EH}_{s,t})} \right)^{\left(-\frac{1}{1-\sigma_{H,s}}\right)} H_{s,t} \quad \forall s \in \mathcal{S}, \tag{23}$$

$$(1+\tau^{EH}_{s,t})P^{H}_{s,t} = \left[\sum_{j=1}^{S} \psi_{H,s,j} \left((1+\tau^{Ec}_{s,j,t})P_{j,t}\right)^{-\frac{\sigma_{H,s}}{\left(1-\sigma_{H,s}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s}\right)}{\sigma_{H,s}}} \quad \forall s \in \mathcal{S}, \tag{24}$$

and

$$(1+\tau^{EH}_{s,t}) = \frac{\left[\sum_{j=1}^{S} \psi_{H,s,j} \left((1+\tau^{Ep}_{j,t})P_{j,t}\right)^{-\frac{\sigma_{H,s}}{\left(1-\sigma_{H,s}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s}\right)}{\sigma_{H,s}}}}{\left[\sum_{j=1}^{S} \psi_{H,s,j} \left(P_{j,t}\right)^{-\frac{\sigma_{H,s}}{\left(1-\sigma_{H,s}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s}\right)}{\sigma_{H,s}}}} \quad \forall s \in \mathcal{S}, \tag{25}$$

the latter representing the implicit (aggregate) tax rate on (all) intermediate inputs of sector s.

3.5 Policy

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

$$TR_t = \tau^{w}_{t} \cdot w_t \cdot N_t + \tau^{c}_{t} \cdot C_t + P^{em}_{t} \cdot \sum_{s=1}^{S} Z_{s,t} + \sum_{s=1}^{S} \tau^{EH}_{s,t} \cdot P^{H}_{s,t} \cdot H_{s,t}. \tag{26}$$

We assume that tax rates are set according to a policy target, and that, when this target is changed, the transition is associated with an AR(1)-process. This implies that for all tax rates $X \in \{\tau^{c}_{s,t}, \tau^{w}_{t}, \tau^{Ec}_{s,t}, \tau^{Ep}_{s,t}, P^{em}_{t}\}_{s\in\mathcal{S}}$, 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. Remember that the rate τ^{c}_{t} and τ^{EH}_{t} are derived endogenously by the above equations (7) and (25). Allowing for public debt and different fiscal rules along the lines of Mitchell, Sault, and Wallis (2000), for example, is possible but would only complicate our analysis. Furthermore, given our representative agent assumption, it does not substantially change the results presented below.

3.6 Market clearing and aggregation

We follow Bouakez et al. (2021) and define CPI-deflated sectoral value added as

$$y^{va}_{s,t} = P_{s,t} \cdot y_{s,t} - (1+\tau^{EH}_{s,t}) \cdot P^{H}_{s,t} \cdot H_{s,t} - \left[\phi_{1,s} \cdot U^{\phi_{2,s}}_{s,t} + P^{em}_{t} \cdot \kappa_s \cdot (1-U_{s,t})\right] y_{s,t},$$

which implies that total value added is given by $Y^{va}_{co,t} = \sum_{s=1}^{S} y^{va}_{s,co,t}$. It must hold that

$$Y^{va}_t = C_t + P^I_t \cdot I_t. \tag{27}$$

The emission stock evolves according to

$$M_t = (1 - \rho^M) \cdot M_{t-1} + \sum_{s=1}^{\mathcal{S}} Z_{s,t}, \tag{28}$$

where $\rho^M \in (0, 1)$ determines how fast additional emissions are relieved. This completes the model description. We will now turn to the model calibration.

4 Calibration

The model calibration consists of three parts. The first comprises the specification of general parameters related to the aggregate economy, mainly taken from the literature. The second set of parameters captures heterogeneity on the production side by allowing for sector-specific factor intensities, input-output linkages, price rigidities and contributions to final demand. The final group of parameters refers to the environmental module of the model, including carbon intensities, abatement costs and economic damage from emissions. We calibrate the model to the EU27 countries plus UK (termed as EU28).

General parameters The model is calibrated to the quarterly frequency. We set the discount factor to $\beta = 0.992$, which implies an annual interest rate of 3.3%. The intertemporal elasticity of substitution is fixed at a standard value of $\sigma_c = 2$. Along the lines of Coenen, Straub, and Trabandt (2013), the Frisch elasticity of labor supply is calibrated to 0.5 (i.e. $\Psi = 2$). The relative weight of the disutility of labor is set to $\kappa_N = 6.3307$ in order to match a targeted aggregate labor supply of $\bar{N} = 0.33$. We assume an annual depreciation rate of 10%, which is a standard choice in the literature (see, for example, Cooley and Prescott, 1995). The fiscal parameters rely on estimates of a standard DSGE model for Germany (Gadatsch, Hauzenberger, and Stähler, 2016). Table 1 summarizes our baseline calibration of general parameters.

Substitution elasticities for goods produced in the different sectors are set as follows. For the consumption basket, we follow Atalay (2017) and Baqaee and Farhi (2019) and choose 0.9. The elasticity of substitution for the investment goods basket is assumed to be a bit lower and set to 0.75. For intermediate inputs, we follow Bouakez et al. (2021) and Atalay (2017) by choosing a value of 0.1. Baqaee and Farhi (2019) allow for a higher substitution elasticity (of 0.4). Using this or even higher values does not change our results qualitatively and only mildly quantitatively (the adjustment of relative prices is just a bit lower). For the substitution elasticities of labor and capital, we opt for high substitutability and set the value to 10. Bouakez et al. (2021) assume perfect substitutability. We do not have to go that far, but when substitutability becomes too low, the system can no longer be solved. Antoszewski (2019) provides a critical discussion.

Sector-specific production parameters On the production side of the economy, we distinguish between $S = 54$ sectors, relying on the standard NACE Rev. 2 classification.[7] We allow for several heterogeneities across sectors. Labor and capital are not perfectly mobile across sectors, represented by $\omega_{N,s}$ and $\omega_{K,s}$, respectively. Furthermore, the production technology of intermediate goods producers differs across sectors as we allow for heterogenous factor intensities for labor, capital and intermediate inputs. Moreover, all sectors contribute differently to final demand. For each sector s, these parameters are derived using the most recent release of the World Input-Output Database (WIOD), covering the years 2000-2014 (see Timmer, Dietzenbacher, Los, Stehrer, and De Vries, 2015).[8] It includes data on socioeconomic accounts as well as input-output tables for 56 sectors and 43 countries. We build an aggregate over the 27 European Union countries plus the UK. While the socioeconomic accounts help us to pin down $\omega_{N,s}$, $\omega_{K,s}$, $\alpha_{N,s}$ and $\alpha_{H,s}$, we can use the provided input-output tables to match inter-sectoral trade shares, $\psi_{H,s,j}$, as well as the sectoral shares in the consumption and investment good bundles, $\psi_{C,s}$ and $\psi_{I,s}$, respectively. In order to determine sector-specific labor and capital supply, we first sum up the number of persons engaged and the nominal capital stock over all sectors, and then compute the respective shares. Dividing the amount of intermediate inputs by gross output per industry yields the factor intensities for intermediate inputs, $1 - \alpha_{H,s}$. In combination with the share of gross output that flows into labor compensation, we can fix the values for $\alpha_{N,s}$. Parameters $\psi_{H,s,j}$ describe the share of intermediate inputs consumed by sector s that are produced by sector j. To obtain these, we first compute the total sum of intermediate inputs for each sector and then the respective shares of the producing sectors, using the input-output tables. Relying on WIOD's national accounts data, the distribution of final consumption expenditure by households and gross fixed capital formation across sectors can be derived, giving us the CES bundle shares $\psi_{C,s}$ and $\psi_{I,s}$. To facilitate calculations, we normalize relative prices to one in the initial steady state. Furthermore, sector-specific price markups are based on findings in Christopoulou and Vermeulen (2012). Sector-specific parameter choices concerning production are summarized in Table 2. Table 3 presents the inter-sectoral linkages regarding intermediate inputs.

Environmental parameters Sector-specific CO2 emissions per unit of output are calibrated using environmental accounts provided by the European Commission that are consistent with the WIOD (see Corsatea et al., 2019). While information on sectoral emissions is available from 2000-2016, we take values from 2014, since the WIOD series on gross output ends in this period and we approximate carbon intensities by dividing emissions by gross output. The stock of pollution decays linearly at a rate of $1 - \rho^{EM} = 0.9979$ as in Heutel (2012) and Annicchiarico and Di Dio (2015). In the abatement cost function, $\phi_{2,s} = 2.8 \, \forall \, s$ as in Nordhaus (2008), while $\phi_{2,s} = 0.185 \, \forall s$ as in Annicchiarico and Di Dio (2015). The parameters of the damage function are either zero (where we discuss the simulations in which we ignore damage) or set to allow for substantial damage.

[7] 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).

[8] Our calibrated steady state values represent mean values over this period. Our calibration tool allows us to extract and aggregate WIOD data for a custom choice of years, country and sector specifications.

Table 1: Baseline calibration of general parameters

Variable/Parameter	Symbol	Value
Discount factor	β	0.992
Elasticity of intertemporal substitution	σ	2.000
Inverse of Frisch elasticity of lab. supply	ζ	2.000
Labor disutility scaling	κ^N	6.331
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	0.9
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	1-1/10
Elasticity of substitution, capital	ν_K	1-1/10
Elasticity of substitution, intermediates	$\sigma_{H,z}$	1-1/0.1000

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

In particular, our parametrization implies that an increase of 10% in the pollution stock relative to its initial steady state level would imply almost a doubling of sectoral output losses. This choice allows us to illustrate the model implications for two rather "extreme" scenarios.[9] Due to the lack of data, we assume abatement cost and damage functions to be equal across sectors. However, further research should focus on sectoral differences and the resulting implications. We abstract from this aspect in the present paper.

What should also be borne in mind is that we assume the parameters of, for instance, the production function (equation 16), the damage function or the factor intensities to be constant over time. This also applies to the entries of the input-output table. However, one of the main results presented below is that the gains from emissions taxes materialize after more than 30 years. It is very likely, though, that structural transformation will take place over a long period such as this, e.g. concerning the production technology. Nonetheless, since these future changes are unknown or highly uncertain, we refrain from ad-hoc adjustments and abstract from this (admittedly important) issue in the present paper. Instead, we also leave this for further research.

[9] The parametrization is loosely tied to Kalkuhl and Wenz (2020). As in Heutel (2012) and Annicchiarico and Di Dio (2015), our model yields pollution stock in arbitrary units, while it tends to be defined over gigatons of carbon in practice. Hence, the coefficients are scaled to keep the proportional output loss consistent. Choosing a lower economic damage from emissions would reduce the damage reduction and thereby reduce and slow down the productivity increase in the simulations shown below. Still, the results do not change qualitatively as long as damage is sufficiently large.

Table 2: Baseline calibration of sector-specific parameters

	$\alpha_{N,s}$	$\alpha_{H,s}$	$\omega_{N,s}$	$\omega_{K,s}$	θ_s^P	$\psi_{C,s}$	$\psi_{I,s}$
1) Crop and animal production, hunting and related service activities	0.669	0.444	0.057	0.021	6.000	0.020	0.003
2) Forestry and logging	0.494	0.591	0.002	0.002	6.000	0.001	0.000
3) Fishing and aquaculture	0.594	0.491	0.001	0.001	6.000	0.001	0.000
4) Mining and quarrying	0.274	0.609	0.004	0.007	6.000	0.001	0.001
5) Manufacture of food products, beverages and tobacco products	0.591	0.254	0.023	0.011	5.348	0.087	0.001
6) Manufacture of textiles, wearing apparel and leather products	0.721	0.318	0.015	0.003	6.882	0.018	0.001
7) Manufacture of wood and of products of wood and cork, except furniture; MF of articles of straw and plaiting materials	0.719	0.302	0.006	0.002	6.556	0.002	0.004
8) Manufacture of paper and paper products	0.591	0.284	0.003	0.003	5.167	0.004	0.000
9) Printing and reproduction of recorded media	0.688	0.413	0.005	0.002	6.263	0.002	0.001
10) Manufacture of coke and refined petroleum products	0.395	0.085	0.001	0.003	9.333	0.019	0.001
11) Manufacture of chemicals and chemical products	0.516	0.274	0.006	0.008	6.882	0.011	0.002
12) Manufacture of basic pharmaceutical products and pharmaceutical prep.	0.330	0.472	0.003	0.005	6.556	0.006	0.002
13) Manufacture of rubber and plastic products	0.662	0.342	0.008	0.004	6.556	0.004	0.003
14) Manufacture of other non-metallic mineral products	0.654	0.349	0.007	0.004	5.545	0.003	0.002
15) Manufacture of basic metals	0.642	0.207	0.005	0.004	5.762	0.001	0.002
16) Manufacture of fabricated metal products, except machinery and equipm.	0.738	0.384	0.018	0.006	7.250	0.004	0.023
17) Manufacture of computer, electronic and optical products	0.531	0.349	0.006	0.006	6.882	0.007	0.025
18) Manufacture of electrical equipment	0.644	0.347	0.007	0.003	6.263	0.006	0.014
19) Manufacture of machinery and equipment n.e.c.	0.674	0.351	0.014	0.006	8.692	0.003	0.069
20) Manufacture of motor vehicles, trailers and semi-trailers	0.627	0.239	0.011	0.008	9.333	0.031	0.053
21) Manufacture of other transport equipment	0.611	0.317	0.004	0.003	12.111	0.003	0.016
22) Manufacture of furniture; other manufacturing	0.733	0.400	0.011	0.003	6.263	0.012	0.014
23) Repair and installation of machinery and equipment	0.785	0.413	0.006	0.002	6.263	0.001	0.023
24) Electricity, gas, steam and air conditioning supply	0.296	0.356	0.006	0.027	4.226	0.029	0.005
25) Water collection, treatment and supply	0.395	0.519	0.002	0.006	5.545	0.005	0.000
26) Sewerage; waste collection, treatment and disposal activities materials recov.; remediation act. & other waste managem. serv.	0.503	0.395	0.005	0.014	5.545	0.008	0.001
27) Construction	0.730	0.378	0.072	0.030	5.762	0.009	0.473
28) Wholesale and retail trade and repair of motor vehicles and motorcyc.	0.671	0.556	0.018	0.004	3.439	0.027	0.011
29) Wholesale trade, except of motor vehicles and motorcycles	0.639	0.506	0.046	0.014	3.857	0.053	0.038
30) Retail trade, except of motor vehicles and motorcycles	0.701	0.600	0.087	0.014	3.381	0.086	0.022
31) Land transport and transport via pipelines	0.693	0.470	0.028	0.022	3.857	0.023	0.004
32) Water transport	0.394	0.288	0.001	0.003	2.282	0.002	0.000
33) Air transport	0.665	0.291	0.002	0.003	2.563	0.009	0.000
34) Warehousing and support activities for transportation	0.564	0.423	0.011	0.021	3.326	0.005	0.002
35) Postal and courier activities	0.889	0.569	0.008	0.003	3.083	0.002	0.000
36) Accommodation and food service activities	0.652	0.518	0.045	0.011	4.846	0.084	0.000
37) Publishing activities	0.624	0.444	0.005	0.002	2.163	0.008	0.008
38) Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting act.	0.552	0.460	0.003	0.004	2.163	0.007	0.007

continued on next page

continued from previous page	$\alpha_{N,s}$	$\alpha_{H,s}$	$\omega_{N,s}$	$\omega_{K,s}$	θ_s^P	$\psi_{C,s}$	$\psi_{I,s}$
39) Telecommunications	0.334	0.494	0.006	0.012	2.163	0.027	0.004
40) Computer programming, consultancy and related activities; information service activities	0.742	0.569	0.014	0.004	2.163	0.003	0.055
41) Financial service activities, except insurance and pension funding	0.560	0.537	0.016	0.011	3.564	0.031	0.002
42) Insurance, reinsurance and pension funding, except compulsory social security	0.474	0.345	0.004	0.005	4.030	0.030	0.001
43) Activities auxiliary to financial services and insurance activities	0.772	0.486	0.007	0.002	3.041	0.002	0.001
44) Real estate activities	0.061	0.756	0.010	0.476	1.300	0.181	0.018
45) Legal and accounting activities; activities of head offices; management consultancy activities	0.723	0.567	0.025	0.005	3.273	0.003	0.016
46) Architectural and engineering activities; technical testing and analysis	0.775	0.536	0.013	0.002	3.273	0.001	0.029
47) Scientific research and development	0.580	0.593	0.005	0.006	1.901	0.000	0.019
48) Advertising and market research	0.633	0.415	0.006	0.001	3.273	0.000	0.000
49) Other professional, scientific and technical activities; veterinary act.	0.729	0.540	0.006	0.001	3.273	0.003	0.001
50) Administrative and support service activities	0.627	0.559	0.054	0.023	2.053	0.013	0.004
51) Public administration and defence; compulsory social security	0.763	0.675	0.068	0.092	10.091	0.006	0.006
52) Education	0.890	0.804	0.067	0.025	10.091	0.016	0.006
53) Human health and social work activities	0.811	0.654	0.096	0.027	10.091	0.037	0.002
54) Other service activities	0.699	0.587	0.043	0.017	2.538	0.045	0.006

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, taking an average over the years 2000-2014. In the baseline simulation, we assume $\kappa_s^P = 0\,\forall s$. Results for staggered price setting are presented in the appendix.

Table 3: Input-Output Matrix, $\psi_{s,j}$

Producer j	**Consumer** s 1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)	12)	13)	14)	15)	16)	17)	18)	19)	20)	21)	22)	23)	24)	25)	26)	27)
1)	24.4	4.4	0.9	0.2	26.1	1.5	0.2	0.1	0.1	0.1	0.4	0.3	1.2	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.2	0.1	0.2	0.1	0.1	0.1
2)	0.1	42.3	0.1	0.1	0.1	0.0	12.7	3.6	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.1	0.0	0.0	0.1
3)	0.1	0.0	6.8	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4)	0.2	0.1	0.3	11.0	0.2	0.1	0.1	0.4	0.1	35.2	1.1	0.2	0.2	3.2	3.5	0.4	0.1	0.3	0.2	0.1	0.1	0.7	0.2	10.6	0.3	0.2	0.5
5)	18.3	0.5	8.0	0.6	23.6	2.0	0.4	1.0	0.4	0.6	2.9	2.0	0.7	0.5	0.4	0.3	0.5	0.4	0.3	0.2	0.2	0.7	0.3	0.3	0.4	0.5	0.3
6)	0.3	0.3	2.7	0.2	0.2	32.6	0.4	1.4	0.4	0.1	0.4	0.4	1.4	0.3	0.2	0.3	0.3	0.3	0.3	0.8	0.5	2.5	0.5	0.1	0.2	0.4	0.3
7)	0.5	2.8	1.2	0.7	0.3	0.3	30.4	1.8	0.3	0.1	0.3	0.2	0.5	0.9	0.3	0.7	0.3	0.4	0.4	0.4	0.9	11.4	0.4	0.3	0.2	0.4	3.1
8)	0.4	0.4	0.5	0.5	1.9	1.0	1.5	31.3	24.8	0.2	1.3	1.4	1.6	1.3	0.3	0.5	0.8	0.9	0.4	0.2	0.3	1.4	0.4	0.3	0.4	1.2	0.2
9)	0.1	0.3	0.2	0.2	0.3	0.4	0.2	2.1	17.3	0.1	0.4	0.7	0.4	0.3	0.2	0.3	0.5	0.4	0.3	0.2	0.2	0.6	0.3	0.2	0.4	0.4	0.2
10)	3.7	3.5	9.6	2.7	0.5	0.6	0.9	0.8	0.4	15.3	6.6	0.9	1.4	2.4	2.2	0.4	0.3	0.5	0.4	0.3	0.3	0.7	0.5	2.4	1.6	1.2	1.0
11)	7.1	1.8	4.7	2.4	1.2	5.5	3.9	5.8	4.7	6.4	32.4	10.1	25.3	4.1	2.8	2.3	2.3	3.0	1.3	1.8	1.4	3.2	1.4	1.7	3.6	1.8	1.3
12)	0.9	0.1	0.7	0.2	0.3	0.3	0.2	0.4	0.3	0.3	1.6	17.0	1.0	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.4	0.1	0.1	0.3	0.2	0.1
13)	0.9	0.6	1.9	1.0	1.8	2.8	1.4	2.3	1.8	0.8	2.4	1.8	16.9	1.7	0.7	2.0	2.9	4.1	3.3	5.6	2.7	4.1	3.5	0.5	0.7	1.1	3.1
14)	0.8	0.5	0.7	2.3	0.8	0.4	1.9	0.3	0.2	1.5	1.0	0.8	1.1	21.4	1.4	1.1	1.2	1.2	0.6	1.0	0.6	1.2	0.9	0.9	0.9	0.8	9.1
15)	0.3	0.4	0.3	1.7	0.2	0.3	0.5	0.5	0.5	0.5	1.3	0.5	1.6	1.9	34.9	22.4	2.7	11.8	9.1	5.9	5.0	4.8	7.0	0.6	1.3	3.8	1.9
16)	1.1	1.1	2.0	3.9	1.1	0.9	2.1	0.9	0.9	0.9	1.3	0.8	2.7	2.2	5.1	26.0	3.8	7.1	15.0	7.6	9.1	5.5	10.1	1.2	2.6	3.1	6.0
17)	0.3	0.4	0.6	0.5	0.2	0.3	0.3	0.4	0.7	0.3	0.4	0.6	0.4	0.4	0.4	0.6	19.1	4.1	1.7	1.0	2.7	1.6	2.7	0.5	0.7	0.4	0.7
18)	0.3	0.3	0.7	0.8	0.2	0.3	0.4	0.3	0.3	0.3	0.4	0.3	0.6	0.6	0.7	1.4	5.0	19.5	4.1	2.6	2.1	1.4	4.5	1.7	1.3	0.6	2.6
19)	1.2	2.0	1.8	3.4	0.6	0.7	1.1	1.2	1.1	0.6	0.8	0.7	1.2	1.5	1.8	3.2	2.7	3.5	19.2	5.2	4.4	1.5	7.7	1.0	3.9	1.9	1.9
20)	0.4	0.8	0.3	0.6	0.2	0.3	0.4	0.2	0.2	0.2	0.3	0.5	0.7	0.5	0.5	0.9	1.1	1.6	3.9	33.5	1.8	0.9	3.0	0.2	0.6	1.3	0.5
21)	0.1	0.2	3.5	0.4	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.3	20.8	0.2	3.6	0.1	0.2	0.3	0.2
22)	0.3	0.4	0.8	0.3	0.2	0.5	1.4	0.2	1.1	0.1	0.3	0.7	0.4	0.4	0.3	0.6	1.2	0.5	0.6	0.5	0.7	9.8	1.2	0.2	0.3	0.3	0.6
23)	1.5	1.2	2.9	4.4	0.4	0.3	0.7	0.9	0.5	0.4	0.8	0.3	0.6	1.0	1.3	1.3	1.3	1.4	2.0	1.4	8.4	0.9	12.2	1.1	1.5	0.9	1.0
24)	3.0	1.4	4.2	9.2	2.5	2.9	3.3	8.4	2.8	3.3	5.1	2.4	3.9	8.5	6.2	2.6	1.5	1.8	1.8	1.3	1.4	1.9	1.8	45.3	12.2	2.4	0.9
25)	0.7	0.1	0.6	0.3	0.3	0.2	0.1	0.3	0.1	0.2	0.3	0.3	0.2	0.3	0.5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	8.9	1.2	0.1
26)	0.6	0.3	0.4	1.1	0.5	0.9	0.9	3.0	0.4	0.7	1.2	1.5	1.7	1.6	9.0	1.0	0.2	0.3	0.3	0.2	0.3	0.5	0.3	0.7	6.6	25.3	0.4
27)	1.6	2.5	2.4	4.8	0.7	1.1	1.2	0.9	1.3	1.9	1.0	1.2	1.0	2.1	1.0	1.4	1.0	1.0	1.2	0.6	1.3	1.3	1.7	3.8	7.4	4.0	31.7
28)	1.6	1.9	1.2	0.9	0.9	1.0	0.8	0.7	0.7	0.6	0.9	0.9	0.9	0.9	0.6	0.8	1.0	0.8	1.1	4.1	1.1	1.0	1.0	0.4	1.1	1.4	0.9
29)	8.4	6.6	8.3	4.9	9.6	12.8	8.6	7.3	7.0	8.1	8.9	9.8	8.1	9.2	7.3	7.2	11.2	9.3	8.0	5.4	6.3	11.3	7.8	3.2	4.0	4.9	5.5
30)	5.0	3.5	5.6	2.5	4.6	6.8	3.4	2.7	3.0	2.6	3.9	4.5	3.4	3.1	2.5	2.8	4.8	3.2	2.8	2.9	2.7	5.3	2.9	1.4	1.6	1.7	2.5
31)	1.8	3.3	2.1	7.4	3.4	3.5	4.9	5.0	2.1	3.7	3.4	2.1	2.9	7.0	3.0	2.0	2.0	2.1	1.9	1.8	1.7	3.3	1.4	3.1	1.1	3.6	1.3
32)	0.1	0.2	1.0	0.7	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
33)	0.1	0.2	0.2	0.5	0.1	0.2	0.1	0.2	0.1	0.1	0.2	0.3	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.1	0.4	0.2	0.3	0.2	0.1	0.3	0.1
34)	0.5	1.0	5.0	2.7	1.8	1.5	2.5	2.6	1.1	2.2	1.7	1.8	1.4	2.3	1.4	1.1	1.4	1.3	1.4	1.3	1.0	1.3	1.0	0.7	1.1	1.1	0.7
35)	0.1	0.2	0.1	0.3	0.2	0.2	0.1	0.2	0.5	0.1	0.4	0.7	0.2	0.3	0.1	0.2	0.4	0.4	0.4	0.1	0.2	0.3	0.3	0.3	0.8	0.5	0.2
36)	0.1	0.3	0.2	0.5	0.3	0.4	0.3	0.2	0.3	0.2	0.3	0.5	0.4	0.4	0.2	0.4	0.8	0.4	0.4	0.2	0.4	0.4	0.5	0.3	0.6	0.4	0.5
37)	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.4	1.9	0.1	0.3	0.8	0.2	0.2	0.1	0.2	0.7	0.2	0.2	0.2	0.3	0.6	0.2	0.2	0.5	0.5	0.1
38)	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.1	1.2	0.1	0.1	0.3	0.1	0.1	0.0	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.3	0.2	0.1
39)	0.4	0.7	1.3	1.1	0.4	0.6	0.5	0.4	0.7	0.4	0.6	0.8	0.5	0.7	0.3	0.6	1.2	0.7	0.6	0.3	0.7	0.7	0.7	1.1	1.8	1.4	0.7
40)	0.2	0.4	0.2	1.1	0.5	0.9	0.5	0.6	1.3	0.6	0.8	1.7	0.6	0.7	0.5	0.8	2.5	1.0	1.0	0.6	1.5	0.9	1.1	0.8	2.0	1.6	0.7
41)	2.8	2.4	4.2	5.0	1.7	2.3	1.8	1.6	2.1	2.1	1.7	2.9	1.7	2.2	1.4	2.0	1.8	1.7	1.7	1.3	2.0	2.2	1.9	2.1	4.3	2.2	2.5
42)	1.1	0.8	2.2	0.7	0.4	0.4	0.4	0.4	0.4	0.3	0.5	0.4	0.4	0.5	0.2	0.3	0.4	0.3	0.3	0.2	0.3	0.4	0.3	0.5	0.9	0.9	0.5
43)	0.2	0.3	0.3	0.2	0.1	0.3	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.4	0.2	0.2
44)	0.5	0.9	0.4	1.2	1.1	1.9	1.5	1.1	2.8	0.8	1.0	1.5	1.5	1.7	0.8	1.8	1.7	1.7	1.6	1.3	1.1	2.1	1.6	1.0	2.0	1.8	2.7
45)	1.0	1.4	2.1	4.3	2.1	2.6	1.5	1.8	2.8	3.1	2.4	3.8	2.6	3.0	1.7	2.2	3.6	3.2	3.5	2.0	2.4	2.4	3.0	2.0	3.7	3.3	2.3
46)	0.4	0.6	0.2	2.5	0.5	0.8	0.7	0.7	0.8	0.7	1.0	1.8	1.1	1.5	0.5	1.1	2.0	1.7	1.3	0.9	2.4	0.8	1.6	1.3	2.6	3.5	3.3
47)	0.2	0.1	0.1	0.6	0.2	0.3	0.1	0.2	0.3	0.2	1.0	5.6	0.8	0.5	0.3	0.3	4.2	0.8	0.7	1.4	2.7	0.6	0.6	0.2	0.4	0.4	0.2
48)	0.2	0.2	0.2	0.6	2.4	1.3	0.4	0.6	1.3	0.5	1.6	3.4	0.7	0.7	0.2	0.5	1.2	0.7	0.5	0.9	0.5	1.7	0.5	0.3	0.5	0.6	0.2
49)	1.4	0.4	0.2	0.7	0.3	0.9	0.3	0.3	0.6	0.2	0.3	0.6	0.3	0.4	0.2	0.4	0.6	0.4	0.4	0.3	0.4	0.8	0.4	0.4	0.6	0.7	0.4
50)	3.6	3.1	2.1	5.7	2.8	2.7	2.5	2.8	5.8	1.6	3.2	6.4	3.5	4.7	2.3	3.6	5.1	3.3	3.3	2.3	4.0	3.5	6.5	2.9	8.9	10.5	5.0
51)	0.3	1.3	0.6	0.9	0.4	0.3	0.6	0.7	0.5	0.6	0.6	0.9	0.5	0.7	1.0	0.4	0.6	0.4	0.4	0.3	0.5	0.4	0.4	2.0	2.1	2.4	0.7
52)	0.2	0.4	0.4	0.3	0.2	0.3	0.1	0.2	0.4	0.2	0.3	1.0	0.2	0.2	0.2	0.2	1.0	0.4	0.3	0.3	0.4	0.3	0.5	0.3	0.5	0.5	0.2
53)	0.1	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.2	0.1
54)	0.4	0.8	2.0	0.8	0.6	0.7	0.5	0.4	0.9	0.5	0.4	0.9	0.4	0.6	0.3	0.4	0.7	0.5	0.4	0.4	0.6	1.0	0.7	0.6	1.4	1.1	0.5

continued on next page

continued from previous page

Producer j	Consumer s 28)	29)	30)	31)	32)	33)	34)	35)	36)	37)	38)	39)	40)	41)	42)	43)	44)	45)	46)	47)	48)	49)	50)	51)	52)	53)	54)
1)	0.1	0.8	0.7	0.1	0.2	0.1	0.1	0.1	3.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.4	0.3	0.4	0.4	0.4
2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3)	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4)	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
5)	0.5	1.6	2.4	0.3	1.1	0.7	0.4	0.6	32.6	0.5	1.1	0.4	0.4	0.2	0.1	0.2	0.2	0.5	0.5	1.3	0.7	1.0	0.7	1.1	3.5	4.1	2.0
6)	0.4	0.5	0.4	0.1	0.3	0.2	0.1	0.2	0.5	0.2	0.6	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.4	0.2	0.4	0.3	0.5	0.6
7)	0.2	0.3	0.2	0.1	0.1	0.1	0.2	0.1	0.3	0.2	0.5	0.1	0.1	0.0	0.0	0.0	0.5	0.1	0.2	0.1	0.2	0.4	0.3	0.1	0.3	0.1	0.8
8)	0.4	0.9	0.9	0.2	0.6	0.1	0.3	0.4	0.5	7.3	1.6	0.3	0.5	0.4	0.3	0.8	0.3	0.7	0.9	0.6	1.0	1.2	0.8	0.8	1.0	0.6	0.6
9)	0.8	0.7	1.4	0.2	0.1	0.2	0.4	1.3	0.5	16.9	3.5	1.2	1.6	1.0	0.9	1.2	0.3	1.4	1.8	1.4	3.5	1.8	1.7	1.4	2.4	0.6	1.7
10)	1.3	2.1	1.3	9.4	9.4	17.3	1.7	1.7	0.7	0.3	0.6	0.4	0.5	0.2	0.3	0.4	0.3	0.6	0.5	0.6	0.5	0.7	0.8	1.2	0.9	0.6	0.8
11)	1.4	0.8	0.6	0.6	0.5	0.7	0.5	0.3	1.0	1.1	1.1	0.3	0.5	0.1	0.1	0.1	0.4	0.3	0.6	1.7	0.4	1.3	0.9	0.6	0.8	1.7	1.4
12)	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.1	0.0	0.1	0.1	0.1	0.2	1.0	0.1	1.3	0.2	0.3	0.3	7.1	0.2
13)	3.6	1.0	1.3	1.4	1.1	0.3	0.6	0.6	0.4	0.6	0.5	1.0	0.4	0.2	0.1	0.2	0.3	0.4	0.7	0.6	0.5	0.8	0.7	0.4	0.4	0.6	0.6
14)	0.8	0.5	0.3	0.3	0.1	0.1	0.2	0.1	0.4	0.1	0.1	0.3	0.1	0.0	0.0	0.1	0.6	0.1	0.3	0.7	0.2	0.4	0.3	0.3	0.6	0.3	0.5
15)	0.5	0.4	0.2	0.4	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.0	0.0	0.0	0.2	0.1	0.3	0.6	0.1	0.4	0.2	0.3	0.1	0.1	0.2
16)	2.1	0.7	0.5	0.6	0.4	0.4	0.6	0.3	0.4	0.4	0.2	0.5	0.4	0.1	0.1	0.1	0.5	0.3	1.0	0.7	0.4	0.6	0.7	1.7	0.5	0.4	0.6
17)	0.5	0.6	0.4	0.3	0.4	0.4	0.3	0.7	0.3	0.8	0.7	3.6	2.4	0.3	0.2	0.3	0.2	0.6	1.1	2.2	0.5	1.1	0.6	1.4	0.8	1.2	0.9
18)	0.9	0.5	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.3	0.3	1.5	0.7	0.1	0.1	0.1	0.3	0.3	0.6	0.9	0.3	0.5	0.5	0.4	0.3	0.2	0.7
19)	2.5	0.7	0.5	0.7	0.5	0.8	0.6	0.5	0.5	0.7	0.4	0.9	0.6	0.1	0.1	0.2	0.3	0.3	1.0	1.0	0.4	0.8	0.7	0.6	0.4	0.4	0.6
20)	13.4	0.5	0.5	2.3	0.2	0.3	0.8	1.1	0.2	0.3	0.3	0.3	0.4	0.1	0.1	0.2	0.2	0.3	0.5	0.9	0.2	0.4	1.0	0.6	0.3	0.3	0.4
21)	0.2	0.1	0.1	0.6	1.1	4.4	0.4	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.0	0.0	0.1	0.1	0.3	1.0	0.1	0.2	0.2	2.5	0.1	0.1	0.2
22)	0.3	0.3	0.3	0.2	0.2	0.5	0.4	0.2	0.5	0.6	0.6	0.4	0.3	0.1	0.1	0.3	0.2	0.2	0.3	0.4	0.3	0.8	0.3	0.5	0.9	2.7	0.9
23)	1.2	0.5	0.3	1.1	1.5	4.2	0.7	0.4	0.2	0.4	0.5	1.3	0.3	0.1	0.1	0.1	0.4	0.2	0.3	0.9	0.2	0.5	0.5	1.0	0.3	0.5	0.4
24)	2.4	1.9	4.8	2.6	0.4	0.6	2.0	3.2	3.2	1.1	2.8	2.0	1.2	1.0	0.6	1.0	3.2	1.4	1.4	1.8	1.1	1.7	1.4	3.6	5.4	3.1	3.7
25)	0.2	0.2	0.2	0.1	0.1	0.0	0.1	0.1	0.4	0.1	0.5	0.1	0.1	0.1	0.2	0.1	0.6	0.1	0.1	0.3	0.0	0.1	0.1	0.6	1.0	0.5	0.6
26)	0.6	0.5	0.8	0.4	0.3	0.3	0.3	0.7	0.8	0.3	0.4	0.3	0.4	0.1	0.1	0.3	1.4	0.5	0.4	0.7	0.5	0.8	0.7	3.2	0.9	1.1	1.1
27)	1.8	2.1	5.8	2.0	1.7	1.3	3.7	3.1	2.6	1.0	2.1	2.7	1.7	1.7	1.8	1.4	24.8	1.5	4.8	3.0	1.1	2.5	1.9	8.2	6.4	2.9	3.2
28)	6.8	1.3	1.6	4.6	0.7	0.9	1.7	2.8	1.0	1.1	0.6	0.8	0.9	0.4	0.5	0.5	0.5	0.5	0.4	0.6	0.5	0.8	1.6	1.0	0.8	0.9	0.9
29)	5.6	9.5	4.4	4.2	4.5	4.9	3.0	2.1	8.7	5.8	3.1	4.5	3.7	1.0	0.6	1.7	1.3	1.9	2.6	3.1	5.3	3.7	3.5	3.3	3.3	7.3	4.0
30)	2.9	1.8	1.9	1.9	1.6	1.6	1.0	1.0	5.2	2.1	1.5	2.1	1.2	0.5	0.4	0.7	0.5	0.8	1.1	1.3	1.8	1.9	1.3	2.5	1.9	4.5	2.3
31)	4.3	11.4	4.7	14.6	2.8	1.8	15.1	6.4	1.4	2.8	1.4	0.9	0.9	0.6	0.5	0.6	0.3	1.0	0.9	1.8	0.9	1.5	1.9	3.1	6.2	1.8	1.7
32)	0.2	0.6	0.1	0.5	8.1	0.3	1.0	0.5	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.2
33)	0.3	0.5	0.3	0.5	0.4	6.1	1.1	3.0	0.2	0.4	0.4	0.2	0.5	0.9	0.5	0.6	0.1	0.5	0.4	0.7	0.4	0.6	2.4	0.7	0.3	0.2	0.6
34)	3.6	11.6	3.2	19.3	35.8	19.4	33.4	11.6	0.9	1.5	0.8	1.6	1.3	0.8	0.4	0.6	0.5	1.1	1.1	1.1	0.7	1.3	2.0	1.0	0.7	0.3	0.9
35)	0.8	1.4	3.0	0.6	0.4	0.5	0.6	18.5	0.6	1.3	0.8	2.9	0.9	2.3	1.6	3.5	0.4	1.2	1.0	0.8	0.7	1.1	1.0	2.2	0.8	0.6	0.9
36)	0.8	1.5	1.5	1.0	0.6	1.6	0.7	0.4	1.4	0.5	1.3	1.0	1.2	0.8	0.8	1.3	0.5	1.4	1.2	1.3	0.8	1.4	3.6	1.4	1.8	2.6	2.1
37)	0.8	0.7	1.0	0.4	0.3	0.5	0.4	0.8	0.5	9.5	1.2	1.1	2.2	1.3	0.9	1.6	0.3	1.2	1.5	2.0	5.4	1.8	1.0	1.5	2.8	0.6	1.8
38)	0.5	0.5	0.7	0.1	0.2	0.2	0.1	0.3	1.0	2.4	25.6	2.0	1.5	0.3	0.2	0.2	0.2	1.1	0.9	1.2	17.8	1.0	0.9	0.3	0.6	0.3	1.6
39)	2.2	2.6	2.3	1.3	0.8	1.1	1.7	6.8	1.9	2.9	6.2	32.1	4.3	4.2	2.2	5.6	1.4	3.1	2.3	2.9	3.6	3.3	3.2	3.4	1.9	1.6	2.6
40)	2.2	2.2	2.1	1.6	1.4	2.3	1.5	4.0	1.2	4.8	3.0	4.3	24.7	5.4	2.8	5.9	0.9	3.7	3.0	4.5	3.0	4.0	2.8	3.0	2.6	1.7	3.0
41)	4.2	4.5	5.6	2.9	2.1	2.0	3.0	3.4	3.3	1.8	2.4	2.6	3.2	28.7	9.1	15.1	24.9	5.8	3.2	2.8	3.2	4.4	3.8	5.5	2.0	2.3	5.0
42)	0.9	0.8	1.1	2.1	1.0	0.9	0.9	0.8	0.5	0.3	0.4	0.8	0.7	0.9	23.3	5.6	1.6	0.9	0.6	0.7	0.4	0.7	1.1	1.1	1.3	0.7	0.7
43)	0.4	0.5	0.4	0.3	0.7	0.5	0.2	0.5	0.2	0.3	0.2	0.6	0.5	13.5	29.2	25.1	0.2	0.6	0.6	0.4	0.9	0.5	0.7	0.4	0.2	0.2	0.4
44)	7.2	7.7	17.0	2.4	2.5	1.6	3.6	3.4	7.6	3.0	3.3	5.6	4.4	6.2	4.2	4.4	11.2	6.7	5.9	5.8	3.9	6.9	4.8	6.3	5.6	4.7	5.3
45)	5.2	6.8	7.3	2.4	2.7	2.0	3.4	2.9	2.9	4.5	4.3	3.6	8.8	10.9	6.5	7.0	7.8	35.4	12.6	7.6	9.7	11.7	9.3	5.6	3.3	3.4	5.4
46)	1.3	1.2	1.2	1.3	0.6	0.6	1.5	1.1	0.8	1.3	1.5	1.3	3.5	1.2	0.9	1.1	2.1	2.6	22.7	4.0	2.3	4.5	2.9	2.1	1.2	1.4	1.6
47)	0.1	0.3	0.1	0.2	0.2	0.2	0.1	0.2	0.1	0.7	0.3	0.8	1.3	0.2	0.2	0.2	0.1	0.3	1.0	9.7	0.3	0.7	0.5	2.5	0.9	0.8	0.3
48)	3.3	2.4	3.7	0.6	0.4	0.8	0.5	1.4	0.8	3.6	2.4	2.5	1.8	1.9	1.5	1.1	0.5	1.9	1.0	0.6	12.6	2.0	1.4	1.0	0.6	0.4	1.9
49)	0.8	1.0	0.9	0.5	0.3	0.4	0.5	0.6	0.5	3.4	1.2	0.9	2.4	1.1	1.1	1.5	0.5	2.0	1.8	1.9	1.7	8.6	1.7	1.2	1.5	0.9	1.3
50)	6.5	8.0	8.0	8.3	8.9	13.0	7.2	7.5	5.7	6.9	8.4	6.2	12.0	7.2	5.3	7.1	5.1	10.5	7.6	14.8	7.0	11.8	28.0	8.6	10.2	7.1	9.8
51)	0.7	0.7	0.8	2.0	0.6	0.9	0.9	0.9	0.5	0.5	0.6	0.5	1.0	0.4	0.4	0.4	2.2	1.5	5.3	1.4	0.9	1.3	1.0	2.6	2.1	0.9	1.0
52)	0.6	0.5	0.6	0.6	0.2	1.1	0.5	1.1	0.3	0.4	0.6	0.8	1.7	1.1	0.6	0.4	0.3	1.3	1.0	4.2	1.0	0.8	0.8	3.7	16.0	1.3	1.1
53)	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.3	0.6	0.1	0.3	0.3	0.1	0.3	0.3	0.1	0.2	0.2	0.7	0.2	1.3	0.2	1.2	0.8	20.2	0.5
54)	1.0	1.1	1.5	0.6	0.6	0.8	0.9	1.3	1.8	3.3	9.2	1.6	1.9	1.6	0.7	0.9	0.7	2.1	1.5	1.5	2.2	2.4	1.9	3.1	2.3	2.4	20.1

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 example, 4.4% of the total intermediates used by the second sector stem from the first sector.) The shares were computed by the authors based on the World Input-Output Database, taking an average over the years 2000-2014.

Table 4: Calibration of environmental parameters

Variable/Parameter	Symbol	Value
Pollution decay	$1-\rho^{EM}$	0.9979
Damage parameter (constant)	$\gamma_{0,s}$	0 or 0.43065
Damage parameter (proportional)	$\gamma_{1,s}$	0 or -3.2731e-05
Damage parameter (quadratic)	$\gamma_{2,s}$	0 or 6.4753e-08
Abatement cost parameter (proportional)	$\phi_{1,s}$	0.185
Abatement cost parameter (potent)	$\phi_{2,s}$	2.8
Carbon intensity:	κ_s	
1) Crop and animal production, hunting and related service activities	κ_1	0.2055
2) Forestry and logging	κ_2	0.0897
3) Fishing and aquaculture	κ_3	0.6671
4) Mining and quarrying	κ_4	0.2938
5) Manufacture of food products, beverages and tobacco products	κ_5	0.0489
6) Manufacture of textiles, wearing apparel and leather products	κ_6	0.0421
7) Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	κ_7	0.0513
8) Manufacture of paper and paper products	κ_8	0.1922
9) Printing and reproduction of recorded media	κ_9	0.0349
10) Manufacture of coke and refined petroleum products	κ_{10}	0.3099
11) Manufacture of chemicals and chemical products	κ_{11}	0.2733
12) Manufacture of basic pharmaceutical products and pharmaceutical preparations	κ_{12}	0.0216
13) Manufacture of rubber and plastic products	κ_{13}	0.0435
14) Manufacture of other non-metallic mineral products	κ_{14}	0.9783
15) Manufacture of basic metals	κ_{15}	0.4917
16) Manufacture of fabricated metal products, except machinery and equipment	κ_{16}	0.0297
17) Manufacture of computer, electronic and optical products	κ_{17}	0.0103
18) Manufacture of electrical equipment	κ_{18}	0.0167
19) Manufacture of machinery and equipment n.e.c.	κ_{19}	0.0147
20) Manufacture of motor vehicles, trailers and semi-trailers	κ_{20}	0.0139
21) Manufacture of other transport equipment	κ_{21}	0.0128
22) Manufacture of furniture; other manufacturing	κ_{22}	0.0226
23) Repair and installation of machinery and equipment	κ_{23}	0.0123
24) Electricity, gas, steam and air conditioning supply	κ_{24}	1.5100
25) Water collection, treatment and supply	κ_{25}	0.0733
26) Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	κ_{26}	0.1522
27) Construction	κ_{27}	0.0315
28) Wholesale and retail trade and repair of motor vehicles and motorcycles	κ_{28}	0.0345
29) Wholesale trade, except of motor vehicles and motorcycles	κ_{29}	0.0277
30) Retail trade, except of motor vehicles and motorcycles	κ_{30}	0.0279
31) Land transport and transport via pipelines	κ_{31}	0.3166
32) Water transport	κ_{32}	0.7944

continued on next page

continued from previous page

Variable/Parameter	Symbol	Value
33) Air transport	κ_{33}	1.0661
34) Warehousing and support activities for transportation	κ_{34}	0.0460
35) Postal and courier activities	κ_{35}	0.0672
36) Accommodation and food service activities	κ_{36}	0.0224
37) Publishing activities	κ_{37}	0.0087
38) Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	κ_{38}	0.0090
39) Telecommunications	κ_{39}	0.0067
40) Computer programming, consultancy and related activities; information service activities	κ_{40}	0.0071
41) Financial service activities, except insurance and pension funding	κ_{41}	0.0051
42) Insurance, reinsurance and pension funding, except compulsory social security	κ_{42}	0.0083
43) Activities auxiliary to financial services and insurance activities	κ_{43}	0.0050
44) Real estate activities	κ_{44}	0.0030
45) Legal and accounting activities; activities of head offices; management consultancy activities	κ_{45}	0.0097
46) Architectural and engineering activities; technical testing and analysis	κ_{46}	0.0114
47) Scientific research and development	κ_{47}	0.0171
48) Advertising and market research	κ_{48}	0.0097
49) Other professional, scientific and technical activities; veterinary activities	κ_{49}	0.0124
50) Administrative and support service activities	κ_{50}	0.0203
51) Public administration and defence; compulsory social security	κ_{51}	0.0226
52) Education	κ_{52}	0.0189
53) Human health and social work activities	κ_{53}	0.0181
54) Other service activities	κ_{54}	0.0238

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.

5 Analysis

In this section, we first present the simulation design, while the results are detailed in a second step. The latter is again split into two parts: The first part is devoted to the macroeconomic effects of the simulated tax shifts, ignoring an emission damage (to identify the basic economic effects of each tax measure), while the second part describes these effects including pollution damage. We complete the section with a welfare comparison of all tax regimes.

5.1 Simulation design

We simulate a reduction in the labor income tax rate τ_t^w by roughly 3 percentage points (PP). This implies that the primary deficit ratio rises by 1 PP ex ante, which is re-financed by a corresponding increase in either (i.) the consumption tax rate $\tau_{s,t}^c \forall s$ of about 1.2 PP, (ii.) the energy tax rate in the production process $\tau_{10,t}^{Ep} = \tau_{24,t}^{Ep}$ of about 25 PP, (iii.) the energy tax rate for the final consumer $\tau_{10,t}^{Ec} = \tau_{24,t}^{Ec}$ of about 10 PP, (iv.) the energy tax rate for producers and final consumers $\tau_{10,t}^{Ec} = \tau_{10,t}^{Ec} = \tau_{24,t}^{Ec} = \tau_{24,t}^{Ec}$ of about 7 PP or (v.) the emissions tax P_t^{em} of about 5 PP. All tax rates adjust with an AR(1)-coefficient of 0.9. A faster (slower) transition of the tax rates does not affect our results qualitatively. As outlined in Section 3.5, ex-post budget stabilization is guaranteed by lump-sum transfers, which also holds along the transition. Ex-post stabilization by a different instrument and/or deficit-financing can be incorporated, which, again, does not really change our results. The resulting tax changes are plotted in Figure 1.

5.2 Simulation results

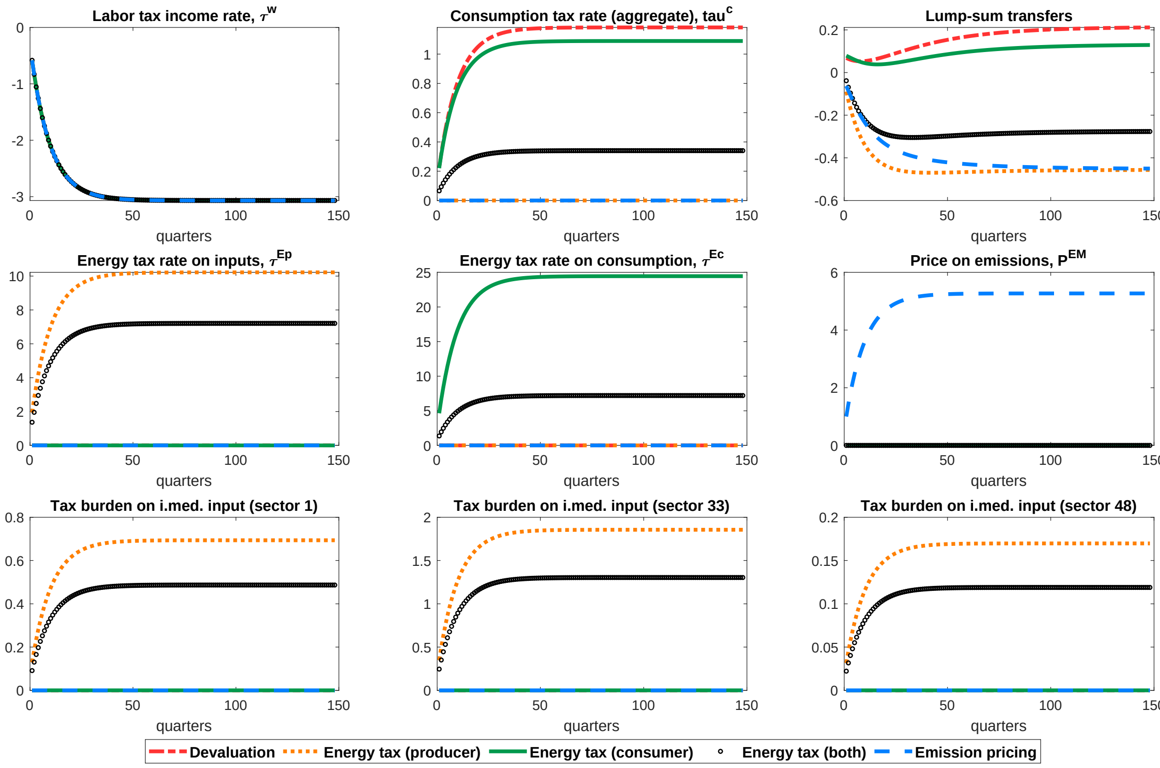
As we can see in Figure 2, financing the labor tax reduction through higher consumption taxation yields the expected effects that have been discussed extensively in the literature (see review above). Lower labor taxation augments the net labor income of households.They accept lower gross wages, which reduces production costs. A decrease in production costs, in turn, allows firms to reduce prices (at least in relative terms), which fosters demand. Higher output needs to be produced by more employment and (at least in the medium term) more capital. As employment rises, so do wages.[10] In turn, higher wage and capital income additionally fosters demand.[11] The positive demand effects are counteracted by a policy-induced rise in consumption costs (see temporary decrease in consumption in Figure 2). However, this effect is not strong enough to compensate for the increase in demand implied by higher income. In addition, given by the AR(1) process, consumption taxation keeps on rising steadily for a while. This temporarily fosters consumption and hampers investment, with the corresponding consequences for capital interest. As we can see in Figure 3, the positive effects are distributed equally across sectors (the corresponding long-run implications in each sector are shown by the blue bars in

[10]Households eventually demand higher wages in exchange for working more, since consumption rises and consumption and leisure are normal goods, too.

[11]In the appendix, we show that, when we allow for staggered price setting, consumer price inflation rises because demand increases more than production does on impact. This induces the central bank to temporarily raise the policy rate. Price rigidities somewhat slow down the transition to the new steady state.

Figure 4). The small deviations (on impact) can be explained by differences in the final consumption and investment baskets, different intermediary inputs and labor intensities, the latter affecting how cost-saving a lower gross wage is in the end (see the corresponding tables in Section 4). In Figure 5, we see that emissions increase, however. This is a result of higher overall production. Long-run effects for aggregate macroeconomic variables are summarized in Table 5.

Figure 1: Implications of tax shift for fiscal variables (no damage)



Notes: Figure plots (projected) implications of tax shifts for fiscal variables (do damage) using colored lines. The red dotted-dashed lines show the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line.

When using energy taxation in the production process (red dotted-dashed line in Figure 2), the macroeconomic effects are much less favourable (see Figure 2). While the positive effects of a labor tax reduction remain, it now becomes more expensive for firms to use energy as input. As we can see in Figure 1, the energy tax rate increases significantly to finance the labor tax reduction. Because every sector needs energy (produced in sectors 10 and 24), the tax burden is shifted away from labor to energy. In the last row of Figure 1, we plot the impact of this hike in energy taxation on the tax costs for intermediate inputs for three arbitrarily chosen sectors. It is clear that sectors which need more energy as input (such as sector 33) face a larger increase in relative production costs than other sectors. Furthermore, a low labor intensity reduces the cost-decreasing effect of the tax shift. In

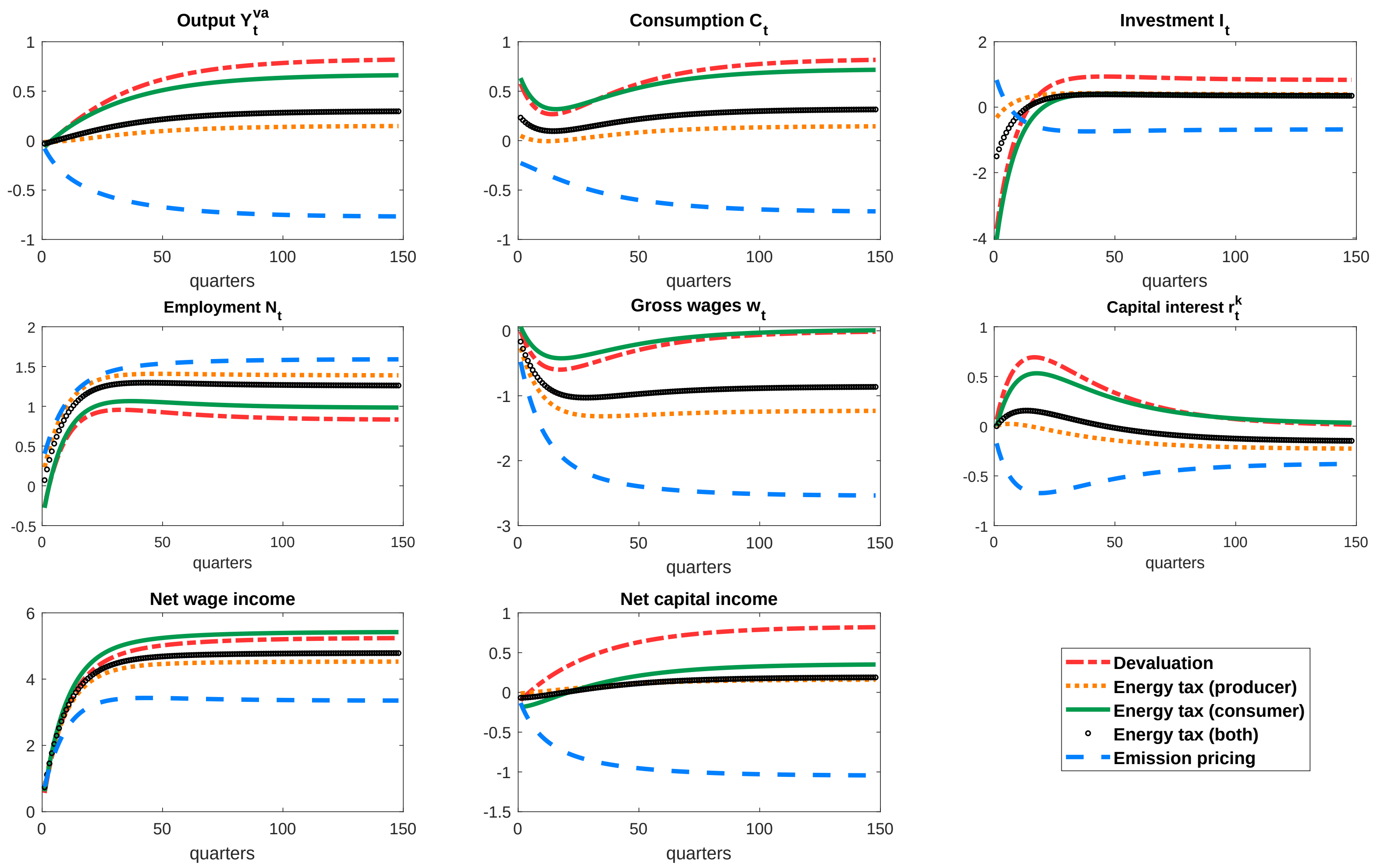
Tables 2 and 3, supported by Figures 3 and 4, we see that besides the two energy sectors (sectors 10 and 24, respectively), manufacturing (especially sectors 11, 13, 14 and 15) as well as transportation (sectors 31, 32 and 33) need a relatively large amount of energy as input and, at the same time, have a relatively low labor intensity (indicated by a small value for $\alpha_{N,s} \cdot \alpha_{H,s}$). On the other side of the spectrum are labor-intensive sectors with relatively little energy input, such as telecommunication, computer or financial services (sectors 39 to 43) as well as administration and research (sectors 45 to 54). These sectors mildly benefit from the tax reform because the labor cost reduction overcompensates for the energy cost increase. The cost push in energy-intensive sectors, however, reduces consumption demand significantly relative to a situation in which consumption taxation is increased. Production becomes more labor-intensive because of relatively lower labor costs. Emissions fall (Figure 5) because particularly emissions-intensive sectors cut down production (see Figures 3 and 4 in combination with Table 4).

When using energy taxes on the final consumption side (green dashed line in Figure 2), the resulting effects in the aggregate (also for the aggregate consumption tax rate) are similar to those when using a general consumption tax to re-finance the labor tax reduction (see Figures 1). This does not come as a surprise because it is the final consumer who bears the cost of the labor tax reduction. What is different, though, is the sectoral impact. In Figure 3, we see that only the two energy sectors (10 and 24) lose significantly, whereas all other sectors increase output. This is because demand shifts away from energy towards other goods as they are relatively cheaper. The shift leads to a somewhat larger fall in emissions (Figure 5) due to the significantly larger drop in output in the energy sectors, whose production is very emissions-intensive (see Table 4).

It appears to be quite plausible that using energy taxation on the production and the consumption side equally, as we did in our fourth simulation, results in a weighted average of the two previously described simulations (black circled lines in the figures). Because of the negative effects when using energy taxation on the production side, however, the measure falls significantly short of a conventional fiscal devaluation.

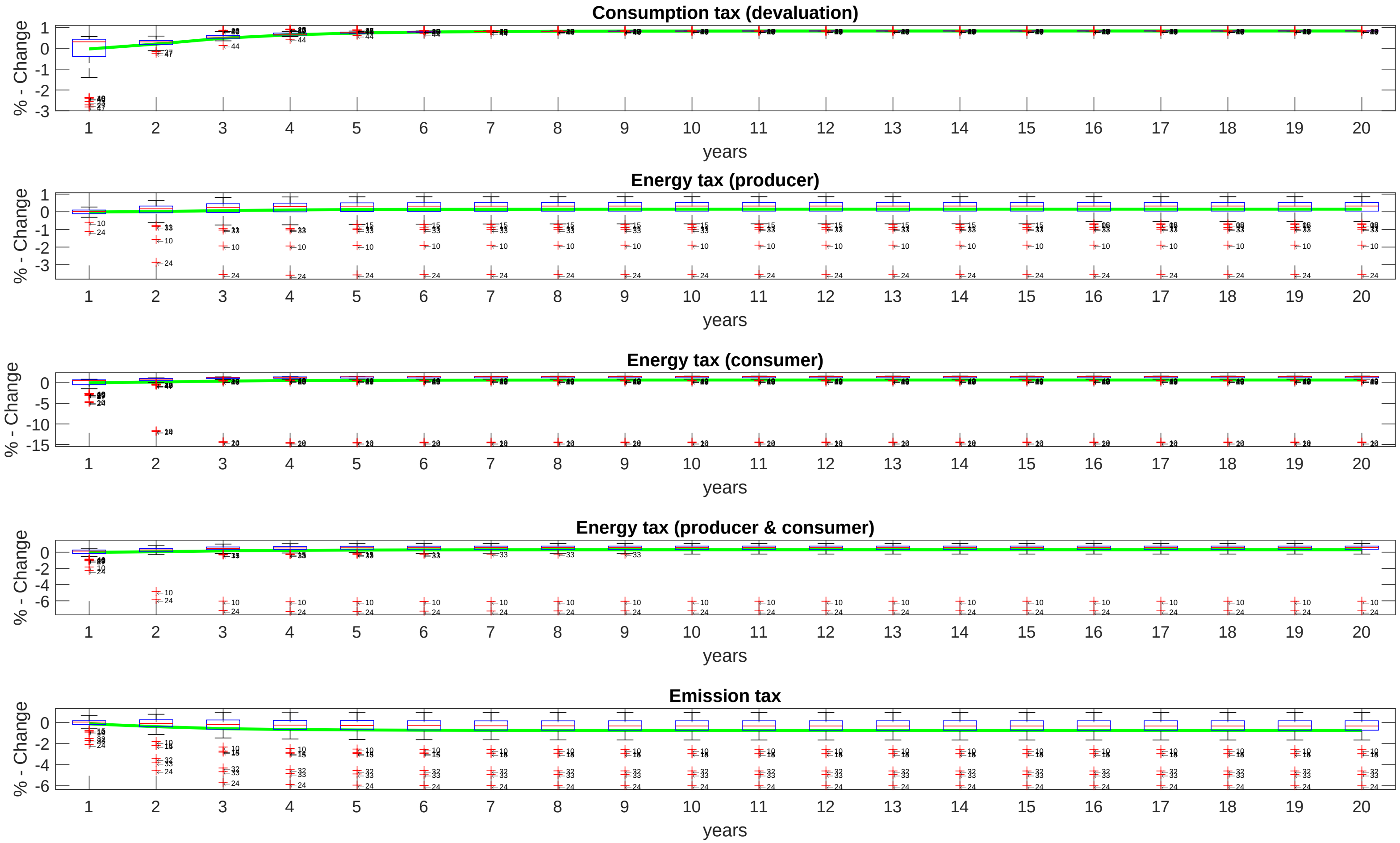
What remains to be analyzed in our first set of simulations is the effect of using emissions taxation to finance the labor tax reduction. The resulting effects are shown by the big-dotted yellow lines in the figures. Similar to taxing energy on the production side, an emission tax increases marginal production costs. This cost increase is not overcompensated for by the production cost reductions stemming from lower labor income taxation (except for the very labor-intensive administration sectors 51 to 54). Hence, the macroeconomic effects are negative (see Figure 2). As every sector is taxed according to its emissions, the effects are more negative than those when using energy taxes only. However, emissions are reduced significantly (see Figure 5). The reason is that firms engage in (less costly) emission abatement to lower their tax burden. It is also true that the energy sectors are affected less negatively (see Figure 3) because the tax burden is now more equally shared between sectors (of course, emissions-intensive sectors still face a higher burden, but for the energy sectors, this is now lower than when facing the burden alone).

Figure 2: Implications of tax shift for key macroeconomic variables (no damage)



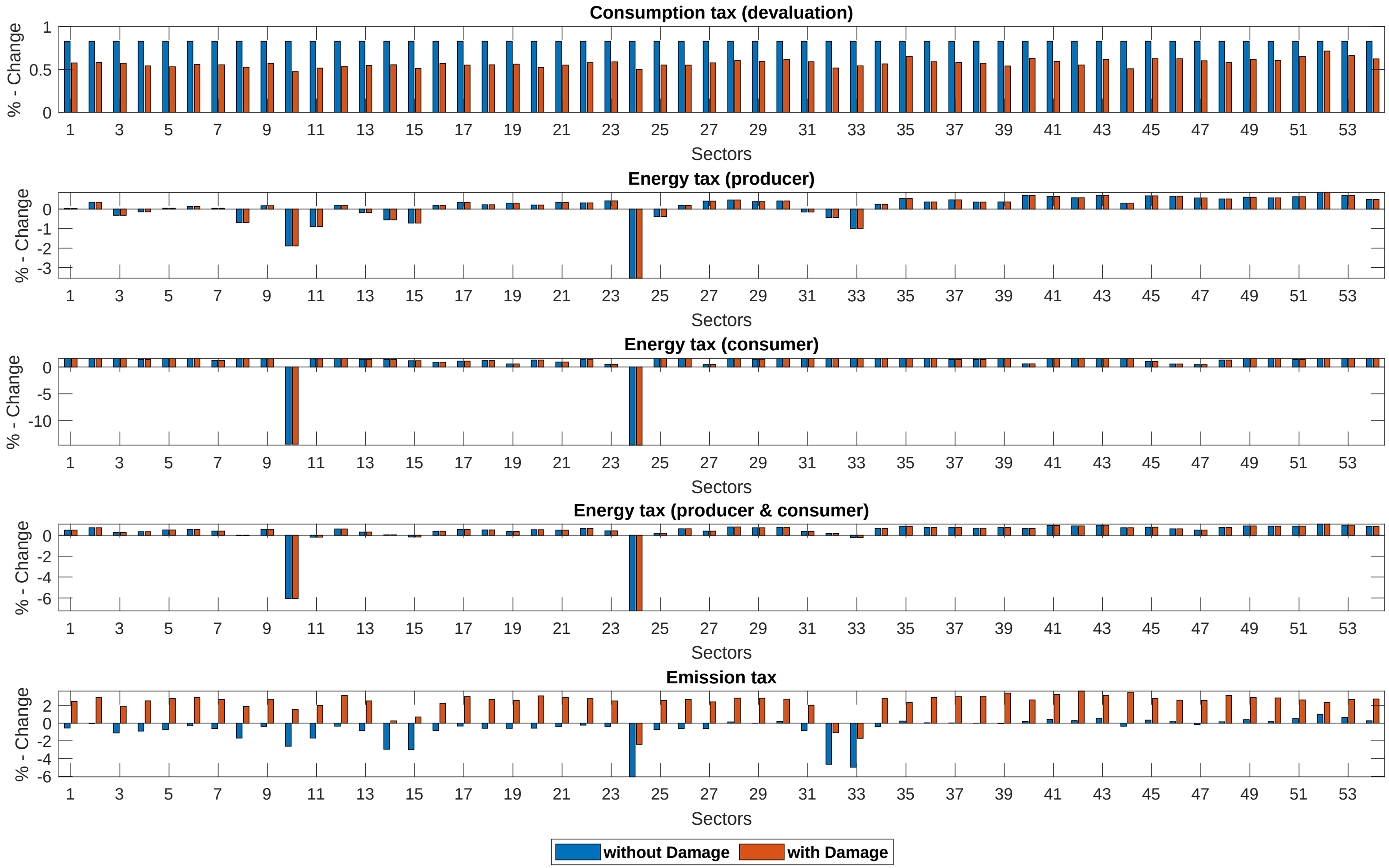
Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in percentage deviation (percentage point deviations for policy rate) from initial steady state, neglecting damage. The red dotted-dashed lines show the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line.

Figure 3: Implications of tax shift for total sectoral output (no damage)



Notes: Figure plots (projected) implications of each tax change for sectoral output (no damage) according to headline. Green solid lines indicate the evolution of aggregate value added, Y_t^{va}. The blue box indicates the average reaction in each sector. The red crosses indicate outliers as indicated by their number in line with Table 2. A time period is one year.

Figure 4: Long-run changes in total sectoral output implied by tax shifts



Notes: Figure plots (projected) percentage deviations of new from initial steady state values of total sectoral output implied by tax shifts without damage (blue bars) and with damage (red bars) according to headline. Sector numbers in line with Table 2.

Overall, we can say that financing a labor tax reduction through higher consumption taxation is superior to all other financing instruments analyzed when abstracting from pollution damages of the economy. The use of emissions taxation even generates negative economic effects. The main reason for this is that the increase in production costs resulting from a policy-induced energy/emissions tax hike cannot (or only to a lesser extent) be compensated for by the production cost decrease that results from lower labor income taxation. This comes at the cost of higher emissions, however. In terms of emission reduction, an emissions tax seems most beneficial, driving down emissions by more than 20%. Ignoring economic damage caused by pollution gives an incomplete picture, however. In what follows, we will therefore discuss how the effects change if we take into account emission damage as described above.

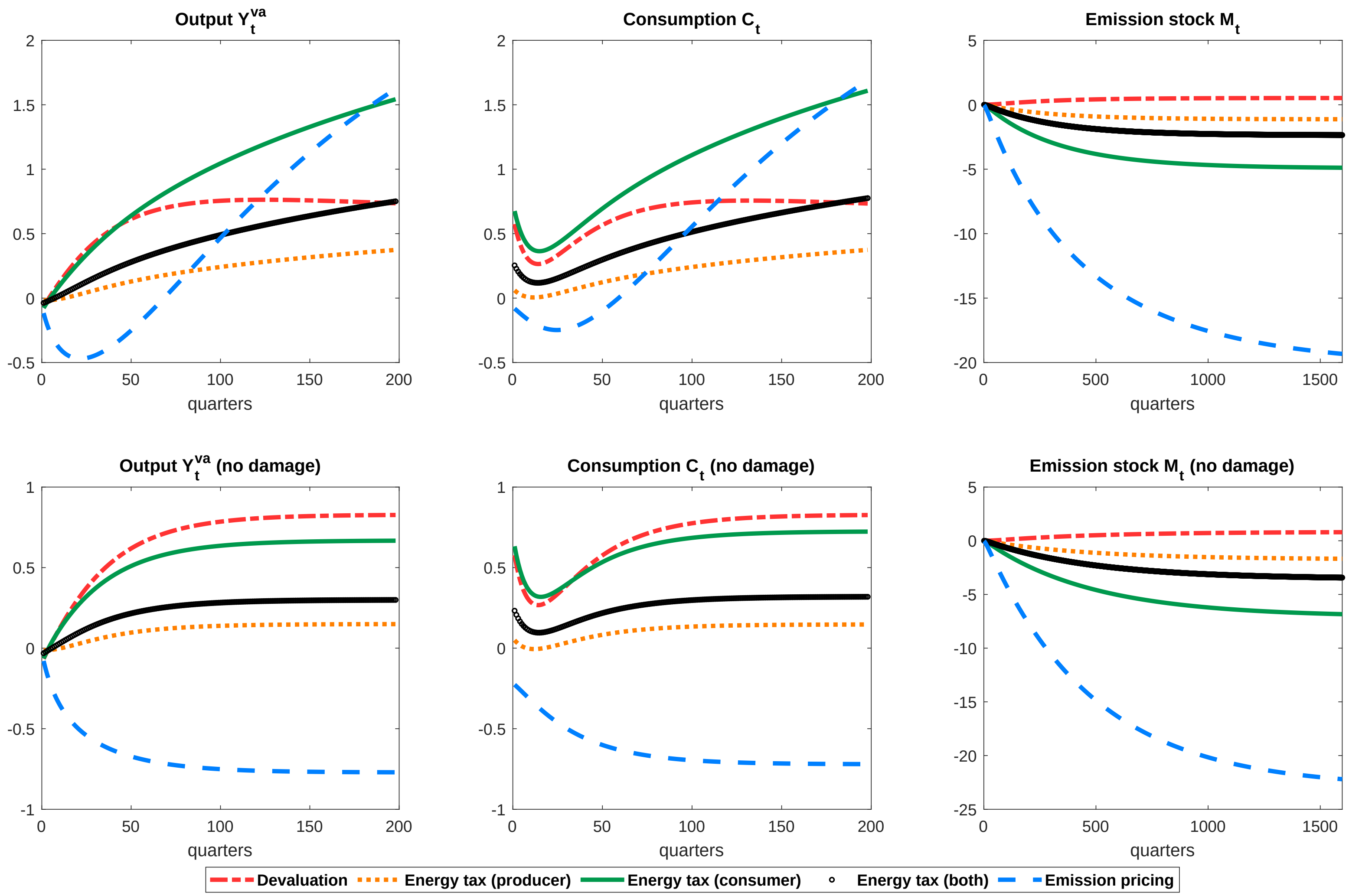
If we take into account the economic damage caused by emissions, the assessment of the financing tools discussed changes. In Figure 5, we compare the results of key variables for the exact same simulation with (upper row) and without (lower row) a damage function (more detailed simulation plots when including the damage function can be found in the appendix). It becomes clear that financing a labor tax reduction through a general consumption tax increase still generates favorable output and consumption effects. The positive impact is now smaller, however. Furthermore, the dampening effects of using energy taxation are also smaller in this case.

Table 5: Long-run effects

Financing instrument:	$\tau^{c}_{s,t}$	$\tau^{Ep}_{10,24,t}$	$\tau^{Ec}_{10,24,t}$	$\tau^{Ep}_{10,24,t}=\tau^{Ec}_{10,24,t}$	P^{em}_{t}
Neglecting damage					
Output	0.83	0.15	0.67	0.30	-0.77
Consumption	0.83	0.15	0.73	0.32	-0.72
Investment	0.83	0.39	0.33	0.35	-0.68
Hours	0.83	1.39	0.98	1.26	1.59
Wages	0.00	-1.23	0.02	-0.86	-2.54
Emissions	0.83	-1.74	-7.08	-3.56	-23.01
With damage					
Output	0.57	0.69	2.70	1.38	2.37
Consumption	0.57	0.69	2.76	1.40	2.42
Investment	0.58	0.90	2.26	1.37	2.30
Hours	0.92	1.21	0.31	0.90	0.55
Wages	-0.35	-0.51	2.73	0.57	1.60
Emissions	0.52	-1.08	-4.93	-2.34	-20.22

Notes: Table shows long-run effects on selected aggregate macro variables of different tax shifts, in percentage deviations from initial steady state.

Figure 5: Comparing results with and without damage



Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables without damage (lower row) and compares these to the same simulations with a damage function (upper row). The damage function follows Heutel (2012).

On impact, the results are fairly comparable. However, as time evolves, using energy and/or emissions taxation as a financing instrument becomes more and more attractive. We see that, unlike when economic damage is neglected, the economic situation tends to continuously improve when damage is taken into account. The use of energy and/or emissions taxation even starts to outperform the use of a general consumption tax as a financing instrument. Depending on which tax we look at, energy/emissions taxes as a financing instrument start outperforming the use of consumption taxes after (more than) 30 years. Furthermore, the positive output and consumption effects tend to be larger when using energy and/or emissions taxes. What is the intuition for this result?

When taking into account emission damage, a reduction in emissions reduces the damage caused by emissions (see Section 3.4). The emission reduction is equivalent to an increase in productivity because it augments total factor productivity (see equation 16). The faster and more strongly emissions fall, the quicker and more effective this effect will be. This fosters the price competitiveness of highly damaged sectors, reduces production costs and, at the same time, increases aggregate income. Demand and output increase, which are typical effects of a productivity increase. In terms of a steady-state comparison (see Table 5), it is therefore clearly favorable to use energy taxes as a financing instrument when taking into account economic damage caused by emissions. The most efficient instrument, at least from a steady-state perspective, is therefore an emissions tax as it creates the largest emissions reduction-induced productivity gain. Here, only the very emissions-intensive energy sector 24, as well as air and water transportation sectors, lose (sectors 32 and 33; see red bars in Figure 4).

As the transition to the new steady state takes time, and because people initially lose when using emissions taxation to finance the labor tax reduction (as they did in the no-damage case), this raises the question of how to evaluate the steady state implications and the transition paths. We seek to answer it within our model by conducting a welfare analysis. In doing so, we compute the lifetime consumption-equivalent gain of the representative household in line with Lucas (2003) as a result of the change in tax policy. The welfare function is given by equation (1). The alternative welfare function is given by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left[(1+ce) \cdot \bar{C}\right]^{1-\sigma}}{1-\sigma} - \kappa_N \frac{\bar{N}^{1+\psi}}{1+\psi} \right],$$

where the bar indicates initial steady-state values. If we equate this equation with equation (1), we can extract the corresponding lifetime consumption-equivalent gain ce. Results are summarized in Table 6.

From the above discussion, it is obvious that financing a labor tax reduction through consumption taxation is the best measure when neglecting economic damage caused by emissions. In turn, if the damage is taken into account, it should be financed by emissions taxes, at least from a pure steady-state perspective. It by far outperforms all other measures in terms of steady-state welfare gains, and even conventional fiscal devaluation in the no-damage case, due to the large emission reduction and the resulting productivity gain.

When taking into account the entire transition path to the new steady state, the positive welfare effects of a conventional fiscal devaluation remain. However, they are slightly smaller as positive consumption gains do not fully realize immediately. When taking into account economic damage and the transition, Table 6 reveals that using energy taxation on the producer side as a financing instrument generates welfare losses. Welfare gains for the use of emissions taxes are significantly reduced. It simply takes too long before the positive effects materialize. None of this is true when taxing energy on the consumer side. In this case, the effects we observe are similar to those of a conventional fiscal devaluation on impact and thereafter. At the same time, we eventually face productivity gains from the emission reduction. Hence, although this measure falls short of using emission taxes in the very long run, the positive effects on impact make this measure the most favorable one from a welfare perspective.

Table 6: Welfare effects

Financing instrument:	$\tau^{c}_{s,t}$	$\tau^{Ep}_{10,24,t}$	$\tau^{Ec}_{10,24,t}$	$\tau^{Ep}_{10,24,t}$=$\tau^{Ec}_{10,24,t}$	P^{em}_{t}
Long-run welfare effects...					
Con. equiv. (no damage)	0.64	-0.17	0.50	0.03	-1.08
Con. equiv. (with damage)	0.35	0.41	2.69	1.19	2.29
...including transition					
Con. equiv. (no damage)	0.46	-0.20	0.38	-0.02	-0.93
Con. equiv. (with damage)	0.41	-0.05	0.90	0.26	0.49

Notes: Table shows welfare implications of different tax shifts, expressed in consumption-equivalent gain for the representative household in line with Lucas (2003), in percentage deviations from initial steady state.

Some words of caution seem warranted, however. First, productivity gains depend heavily on assumptions regarding emission creation and the damage function. On the one hand, a faster decay factor or a higher emission damage, for example, increases the speed/magnitude of emission reductions and thus shortens the period of negative economic effects when using energy and/or emissions taxes as a financing instrument. On the other hand, emissions are not only produced inside the EU28 region. If emissions in other world regions remain fairly constant or even increase, the policy measures analyzed here may not lead to such large damage reductions (or productivity gains, respectively) as we have here as a result. The more this is the case, the more we move towards the no damage scenario (or even worse, if emissions in the rest of the world increase too much).

Second, our welfare conclusions are based on a representative household in the economy. This household faces a policy-induced cost increase resulting from energy taxation, but also obtains the resulting (productivity) gains. While this may hold in the aggregate, it may not be true for all individuals in an economy. As already mentioned in the introduction, in a heterogenous agent framework, low-income households or those who depend heavily on transfers may actually lose. The same is true where relatively poor households tend to be employed in emission and energy-intensive sectors. All this could change the welfare ranking.

Third, the welfare ranking is also subject to structural parameter choices in the production and demand functions. If the need to use energy in production, for example, falls, this changes emissions and thereby damage and its impact. This is also true if we assume that substitutability between production inputs increases. In this latter case, the benefits of taxing energy for final consumers, relative to taxing it in the production process, shrinks (but we still need an implausibly high elasticity in the production process for the ranking to change). As discussed in Section 4, it is likely that some of these parameters will change in the future. And, of course, this also holds for the exact specification of the damage function.

6 Conclusions

This study introduces *EMuSe*, an environmental dynamic multi-sector general equilibrium model in which multiple interrelated production sectors that vary in their factor intensities, use of intermediate inputs, emission creation and contribution to final demand interact with each other in order to analyze the effects of financing a labor tax reduction through higher consumption, energy or emissions taxation. Using *EMuSe* to assess this question is insightful because different production sectors use the output of other production sectors as inputs; through this channel, taxes which supposedly leave many sectors unaffected (such as an energy tax) spill over to the entire economy.

More specifically, we show that when ignoring environmental damage caused by emissions, financing the labor tax reduction through higher consumption taxes is most beneficial in terms of economic performance and welfare. In that case, taxing final consumption generates the lowest distortions in the system. If environmental damage is high enough, using energy and emissions taxes as a financing instrument eventually outperforms the use of consumption taxes due to a positive "productivity-like" shock. However, it takes time before the positive effects materialize. Manufacturing, transportation and energy production sectors tend to lose (gain only a little) while administration, services and research sectors benefit from using environmental taxation as a financing instrument.

In terms of welfare, the implementation of final energy consumption taxation as a financing instrument turns out to be the most beneficial tax in our simulations. The reason is that it generates relatively few distortions on the production side and a sufficient reduction in demand for emissions-intensive energy production such that pollution-induced damages shrink. The negative effects on impact are basically limited to the energy sectors, while the other sectors tend to benefit.

References

Angelopoulos, K., G. Economides, and A. Philippopoulos (2013). First- and second-best allocations under economic and environmental uncertainty. *International Tax and Public Finance 20*(3), 360–380.

Annicchiarico, B., S. Carattini, C. Fischer, and G. Heutel (2021). Business Cycles and Environmental Policy: Literature Review and Policy Implications. NBER Working Papers 29032, National Bureau of Economic Research, Inc.

Annicchiarico, B., L. Correani, and F. Di Dio (2018). Environmental policy and endogenous market structure. *Resource and Energy Economics 52*(C), 186–215.

Annicchiarico, B. and F. Di Dio (2015). Environmental policy and macroeconomic dynamics in a new Keynesian model. *Journal of Environmental Economics and Management 69*(C), 1–21.

Annicchiarico, B. and F. Diluiso (2019). International transmission of the business cycle and environmental policy. *Resource and Energy Economics 58*(C).

Annicchiarico, B., F. Dio, and F. Felici (2015). Fiscal Devaluation Scenarios: A Quantitative Assessment for the Italian Economy. *Open Economies Review 26*(4), 731–785.

Antosiewicz, M., P. Lewandowski, and J. Witajewski-Baltvilks (2016). Input vs. Output Taxation – A DSGE Approach to Modelling Resource Decoupling. *Sustainability 8*(4), 1–17.

Antoszewski, M. (2019). Wide-range estimation of various substitution elasticities for CES production functions at the sectoral level. *Energy Economics 83*(C), 272–289.

Atalay, E. (2017). How Important Are Sectoral Shocks? *American Economic Journal: Macroeconomics 9*(4), 254–280.

Attinasi, M.-G., D. Prammer, N. Stähler, M. Tasso, and S. van Parys (2019). Budget-Neutral Labor Tax Wedge Reductions: A Simulation-Based Analysis for the Euro Area. *International Journal of Central Banking 15*(4), 1–54.

Baqaee, D. and E. Farhi (2019). Networks, Barriers, and Trade. NBER Working Papers 26108, National Bureau of Economic Research, Inc.

Baqaee, D. and E. Farhi (2020). Supply and Demand in Disaggregated Keynesian Economies with an Application to the Covid-19 Crisis. NBER Working Papers 27152, National Bureau of Economic Research, Inc.

Bielecki, M. and N. Stähler (2020). Labor Tax Reductions in Europe: The Role of Property Taxation. *Macroeconomic Dynamics forthcoming*.

Blazquez, J., M. Galeotti, B. Manzano, A. Pierru, and S. Pradhan (2019). K-DSGE: A Dynamic Stochastic General Equilibrium Model for Saudi Arabia. Methodology Papers ks–2019-mp06, King Abdullah Petroleum Studies and Research Center.

Blazquez, J., M. Galeotti, B. Manzano, A. Pierru, and S. Pradhan (2021). Effects of Saudi Arabia's economic reforms: Insights from a DSGE model. *Economic Modelling 95*(C), 145–169.

Böhringer, C. and C. Fischer (2020). Kill Bill or Tax: An Analysis of Alternative CO2 Price Floor Options for EU Member States. CESifo Working Paper Series 8631, CESifo.

Böhringer, C., C. Fischer, and K. E. Rosendahl (2014). Cost-effective unilateral climate policy design: Size matters. *Journal of Environmental Economics and Management 67*(3), 318–339.

Boscá, J. E., R. Doménech, and J. Ferri (2013). Fiscal Devaluations in EMU. *Hacienda Pública Española 206*(3), 27–56.

Bouakez, H., E. Cardia, and F. Ruge-Murcia (2014). Sectoral price rigidity and aggregate dynamics. *European Economic Review 65*(C), 1–22.

Bouakez, H., E. Cardia, and F. J. Ruge-Murcia (2011). Durable goods, inter-sectoral linkages and monetary policy. *Journal of Economic Dynamics and Control 35*(5), 730–745.

Bouakez, H., O. Rachedi, and E. Santoro (2021). The Government Spending Multiplier in a Multi-Sector Economy. *American Economic Journal: Macroeconomics*, accepted.

Burgert, M. and W. Roeger (2014). Fiscal Devaluation: Efficiency and Equity. Technical Report 542, Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.

Burlon, L., A. Notarpietro, and M. Pisani (2021). Fiscal devaluation and labor market frictions in a monetary union. *Economic Modelling 97*(C), 135–156.

Cai, Y. (2020). The Role of Uncertainty in Controlling Climate Change. Papers 2003.01615, arXiv.org.

Cai, Y. and T. S. Lontzek (2019). The Social Cost of Carbon with Economic and Climate Risks. *Journal of Political Economy 127*(6), 2684–2734.

Calvo, G. A. (1983). Staggered prices in a utility-maximizing framework. *Journal of Monetary Economics 12*(3), 383–398.

Chan, Y. T. (2020). Collaborative Optimal Carbon Tax Rate under Economic and Energy Price Shocks: A Dynamic Stochastic General Equilibrium Model Approach. *Journal of Cleaner Production 256*, 120542.

Chang, J., J. Chen, J. Shieh, and C. Lai (2009). Optimal Tax Policy, Market Imperfections, and Environmental Externalities in a Dynamic Optimizing Macro Model. *Journal of Public Economic Theory 11*(4), 623–651.

Christopoulou, R. and P. Vermeulen (2012). Markups in the Euro area and the US over the period 1981-2004: a comparison of 50 sectors. *Empirical Economics 42*(1), 53–77.

Coenen, G., R. Straub, and M. Trabandt (2013). Gauging the effects of fiscal stimulus packages in the euro area. *Journal of Economic Dynamics and Control 37*(2), 367–386.

Cooley, T. and E. Prescott (1995). Economic Growth and Business Cycles. In T. Cooley (Ed.), *Frontiers in Business Cycle Research*, pp. 1–38. Princeton University Press, Princeton University, NJ.

Corsatea, T. D., S. Lindner, I. Arto, M. V. Roman, J. M. Rueda-Cantuche, A. V. Afonso, A. F. Amores, F. Neuwahl, et al. (2019). World Input-Output Database Environmental Accounts. Update 2000-2016. Technical report, Publications Office of the European Union, Luxembourg.

Devulder, A. and N. Lisack (2020). Carbon Tax in a Production Network: Propagation and Sectoral Incidence. Working papers 760, Banque de France.

Duan, Y., T. Ji, Y. Lu, and S. Wang (2021). Environmental regulations and international trade: A quantitative economic analysis of world pollution emissions. *Journal of Public Economics 203*, 104521.

Engler, P., G. Ganelli, J. Tervala, and S. Voigts (2017). Fiscal Devaluation in a Monetary Union. *IMF Economic Review 65*(2), 241–272.

European Commission (2013). Tax Reforms in EU Member States - Tax Policy Challenges for Economic Growth and Fiscal Sustainability. Technical Report 5/2013, European Economy, Brussels.

European Commission (2014). Taxation Trends in the European Union. Technical report.

European Commission (2015). Tax Reforms in EU Member States - Tax Policy Challenges for Economic Growth and Fiscal Sustainability. Technical Report 8/2015, European Economy, Brussels.

European Commission (2016). The Economic Impact of Selected Structural Reform Measures in Italy, France, Spain and Portugal. Technical Report No. 023, European Economy, Brussels.

European Commission (2019). Restructuring the Community Framework for the Taxation of Energy Products and Electricity. Technical Report No. 332 final, Commission Staff Working Document, Brussels.

Farhi, E., G. Gopinath, and O. Itskhoki (2014). Fiscal Devaluations. *The Review of Economic Studies 81*(2), 725–760.

Fischer, C. and M. Springborn (2011). Emissions targets and the real business cycle: Intensity targets versus caps or taxes. *Journal of Environmental Economics and Management 62*(3), 352–366.

Gadatsch, N., K. Hauzenberger, and N. Stähler (2016). Fiscal policy during the crisis: A look on Germany and the Euro area with GEAR. *Economic Modelling 52*(PB), 997–1016.

Gadatsch, N., N. Stähler, and B. Weigert (2016). German labor market and fiscal reforms 1999-2008: Can they be blamed for intra-euro area imbalances? *Journal of Macroeconomics 50*(Supplement C), 307–324.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica 82*(1), 41–88.

Gomes, S., P. Jacquinot, and M. Pisani (2016). Fiscal devaluation in the euro area: A model-based analysis. *Economic Modelling 52*(Part A), 58–70.

Heutel, G. (2012). How Should Environmental Policy Respond to Business Cycles? Optimal Policy under Persistent Productivity Shocks. *Review of Economic Dynamics 15*(2), 244–264.

IMF (2014). Fiscal Monitor 2013 Taxing Times. Technical report, International Monetary Fund, World Economic and Financial Surveys, Washington.

IMF (2020). EU Climate Mitigation Policy. Technical report, International Monetary Fund, Departmental Paper Series, No 20/13, Washington.

Jacquinot, P., M. Lozej, and M. Pisani (2018). Labor tax reforms, cross-country coordination, and the monetary policy stance in the euro area: A structural model-based approach. *International Journal of Central Banking June*, 65–140.

Kalkuhl, M. and L. Wenz (2020). The Impact of Climate Conditions on Economic Production. Evidence from a Global Panel of Regions. *Journal of Environmental Economics and Management 102360.*

Kaufmann, C. (2019). Optimal fiscal substitutes for the exchange rate in monetary unions. *Journal of Economic Dynamics and Control 103*(C), 43–62.

Khan, H., K. Metaxoglou, C. R. Knittel, and M. Papineau (2019). Carbon emissions and business cycles. *Journal of Macroeconomics 60*(C), 1–19.

Lipińska, A. and L. von Thadden (2019). On the Effectiveness of Fiscal Devaluations in a Monetary Union. *Macroeconomic Dynamics 23*(8), 3424–3456.

Lucas, R. E. (2003). Macroeconomic Priorities. *American Economic Review 93*(1), 1–14.

Mitchell, P. R., J. E. Sault, and K. F. Wallis (2000). Fiscal policy rules in macroeconomic models: principles and practice. *Economic Modelling 17*(2), 171–193.

Mora-Sanguinetti, J. S. and M. Rubio (2014). Recent reforms in Spanish housing markets: An evaluation using a DSGE model. *Economic Modelling 44*(Supplement 1), S42–S49.

Nordhaus, W. (2008). *A Question of Balance: Weighing the Options on Global Warming Policies.* New Haven and London: Yale University Press.

OECD (2012). OECD Economic Surveys: Spain 2012. Technical report, OECD Publishing, Paris.

OECD (2015). OECD Economic Surveys: Italy 2015. Technical report, OECD Publishing, Paris.

OECD (2019). Taxing Energy Use 2019: Using Taxes for Climate Action. Technical report, OECD Publishing, Paris.

OECD (2021). Taxing Energy Use for Sustainable Development. Technical report, OECD Publishing, Paris.

Pasten, E., R. Schoenle, and M. Weber (2020). The propagation of monetary policy shocks in a heterogeneous production economy. *Journal of Monetary Economics 116*(C), 1–22.

Ruppert, K., M. Schön, and N. Stähler (2021). Consumption Taxation to Finance Pension Payments. Discussion Papers forthcoming, Deutsche Bundesbank.

Stähler, N. (2019). Who benefits from using property taxes to finance a labor tax wedge reduction? *Journal of Housing Economics 46*(C).

Stähler, N. and C. Thomas (2012). FiMod - A DSGE model for fiscal policy simulations. *Economic Modelling 29*(2), 239–261.

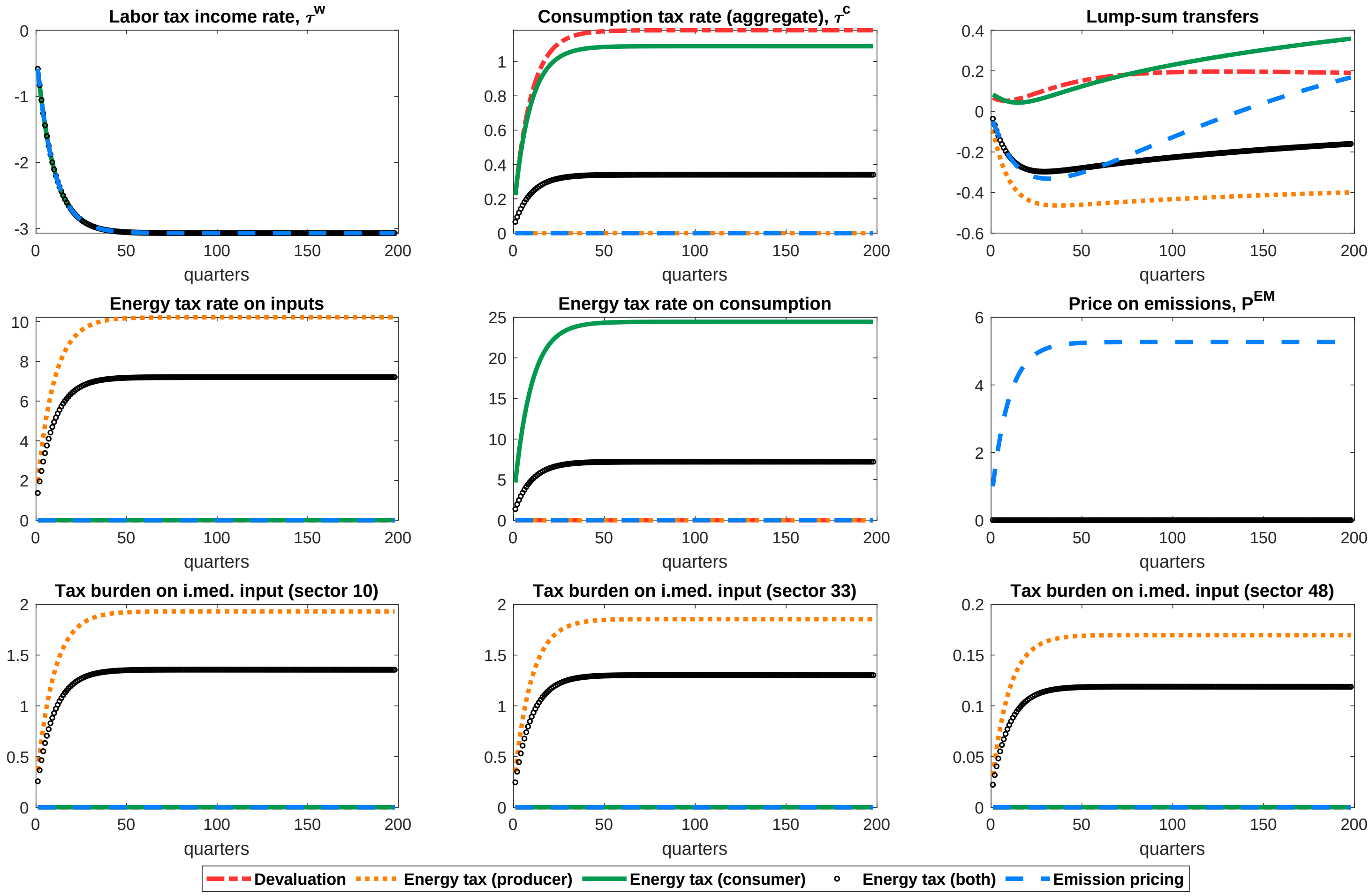
Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. De Vries (2015). An illustrated user guide to the world input–output database: the case of global automotive production. *Review of International Economics 23*(3), 575–605.

Wendner, R. (2001). An applied dynamic general equilibrium model of environmental tax reforms and pension policy. *Journal of Policy Modeling 23*(1), 25–50.

Appendix A: Additional simulation results in a model with damage

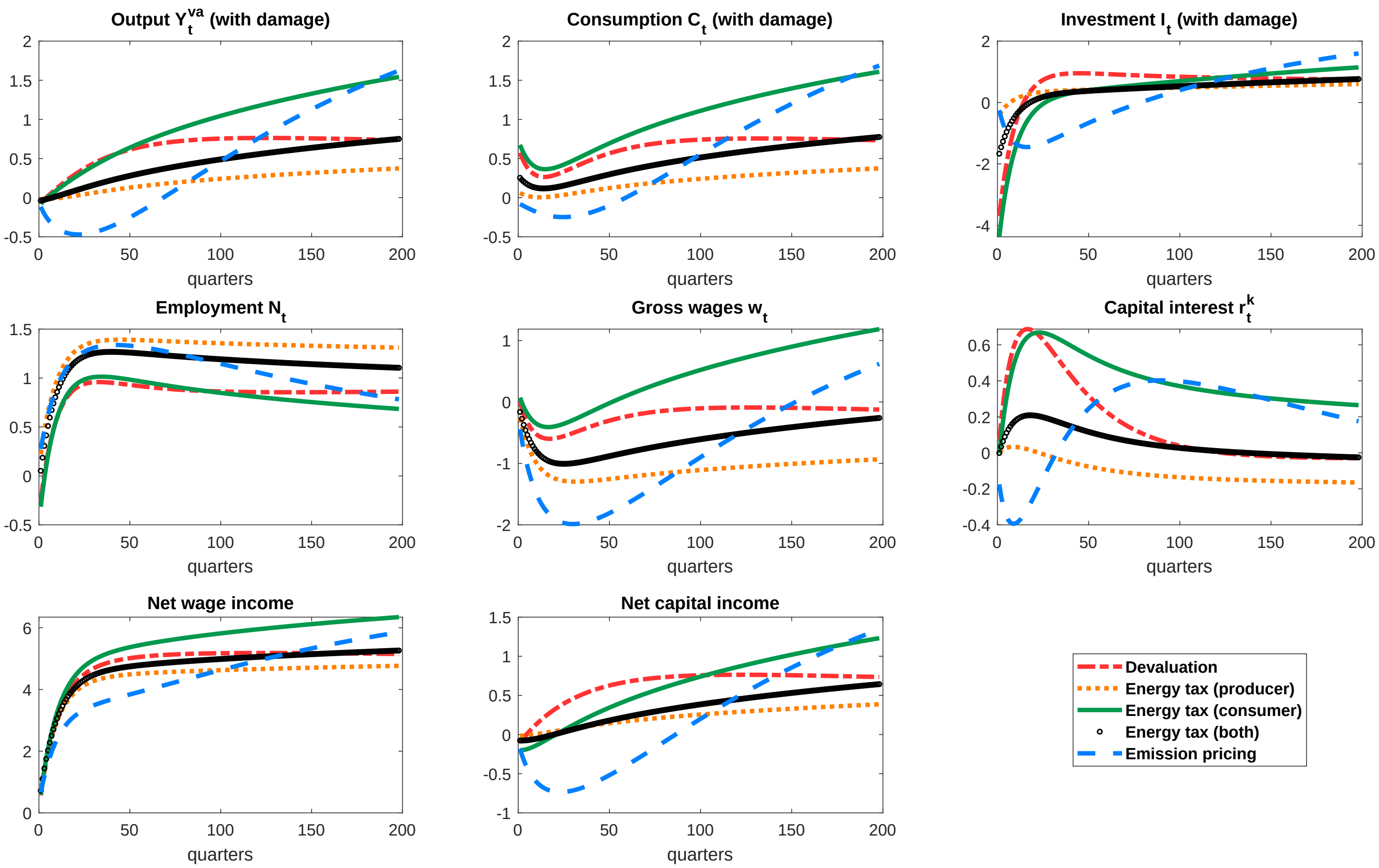
In this Appendix, we show how the economy evolves in the positive damage case, as mentioned in the main text. To be more precise, we repeat the simulations in a model with damage and replicate Figures 1 to 3 in Figure A.1 to A.3.

Figure A.1: Implications of tax shift for fiscal variables (with damage)



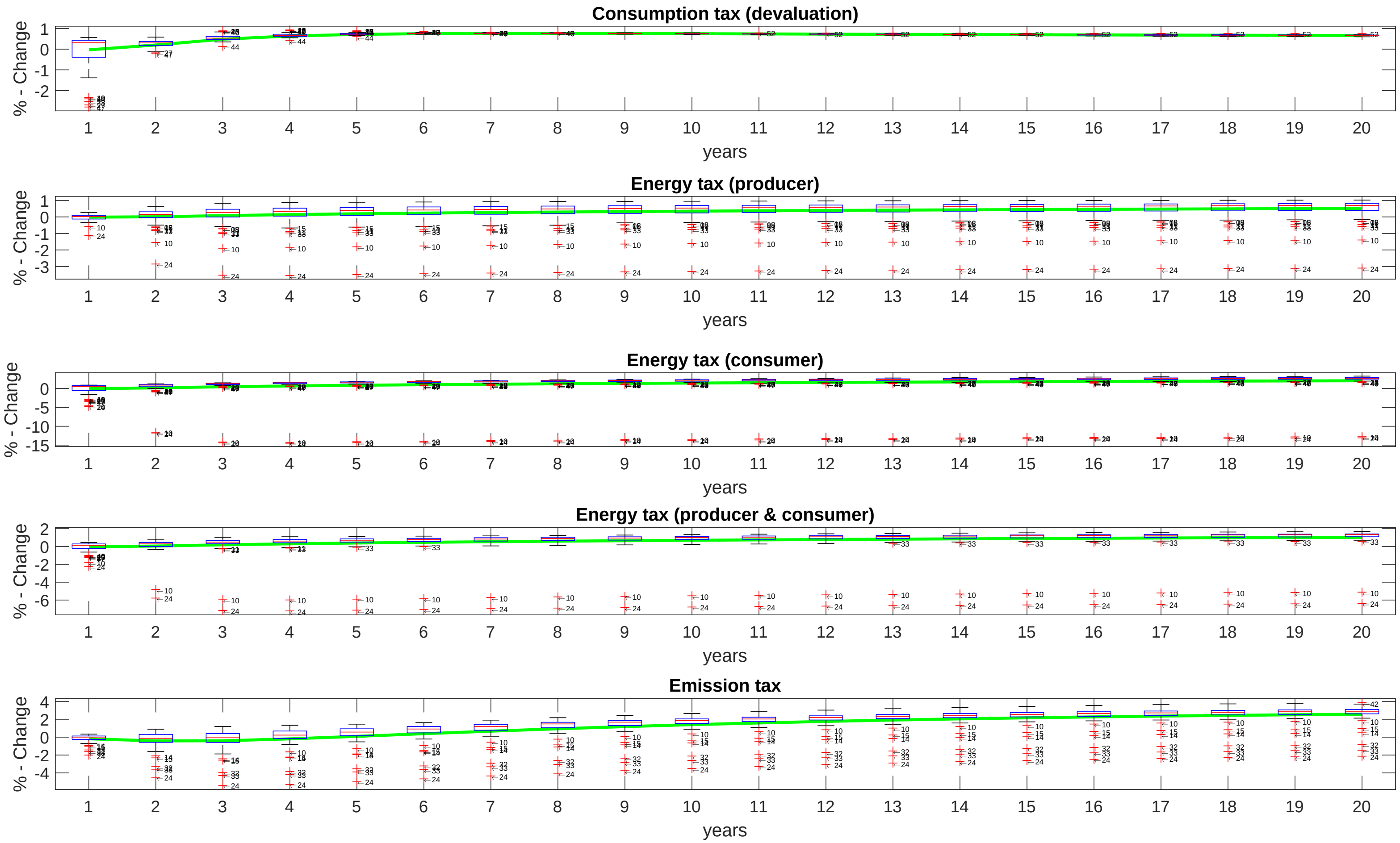
Notes: Figure plots (projected) implications of tax shifts for fiscal variables (with damage) according to colored lines.The red dotted-dashed lines show the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line. The only variable endogenously adjusting here is lump-sum taxation (for the no-damage simulation).

Figure A.2: Implications of tax shift for key macroeconomic variables (with damage)



Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in percentage deviation (percentage point deviations for policy rate) from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line.

Figure A.3: Implications of tax shift for total sectoral output (with damage)



Notes: Figure plots (projected) implications of each tax change for sectoral output (with damage) according to headline. Green solid lines indicate the evolution of aggregate value added, Y_t^{va}. The blue box indicates the average reaction in each sector. The red crosses indicate outliers as indicated by their number in line with Table 2. A time period is one year.

Appendix B: Simulation results in a model with staggered price setting

In this appendix, we show the simulation results for selected macroeconomic variables of including positive price rigidities in Figures B.1 and B.3 when neglecting and taking into account economic damage from emissions, respectively. Staggered price setting mildly postpones the transition process such that emissions taxation starts dominating later.[12] This implies that, when using emissions taxation, welfare is somewhat reduced when taking into account staggered price setting (see Table B.1).

The resulting evolution of producer price inflation (in selected sectors) and consumer price inflation is shown in Figures B.2 and B.4. We see that, as discussed in the main text, labor-intensive sectors that need relatively few energy-intensive goods as input or produce little emissions gain, while the others lose. This translates into a decrease and an increase in producer price inflation and makes these goods relatively less/more expensive. Staggered price setting postpones the transition process slightly, but not much during the time span.

To introduce staggered price setting into our model, we first define CPI inflation $\pi_t^{cpi} = P_t^C / P_{t-1}^C$ and assume that there is a central bank that sets a nominal (benchmark) interest rate R_t in the economy. By the no-arbitrage condition, it must then hold that $\frac{R_t}{\pi_t^{cpi}} = \frac{r_{t+1}^k + (1-\delta) P_{t+1}^I}{P_t^I}$, see also equation (4). From consumption bundling (Section 3.2), we know that CPI inflation can also be expressed as $\pi_t^{cpi} = \left[\sum_{s=1}^S \psi_{C,s} (\pi_{s,t}^{PPI} P_{s,t-1})^{-\frac{(\sigma_C)}{1-\sigma_C}} \right]^{-\frac{(1-\sigma_C)}{\sigma_C}}$. The producer price inflation of sector s, $\pi_{s,t}^{PPI}$, is given by maximizing

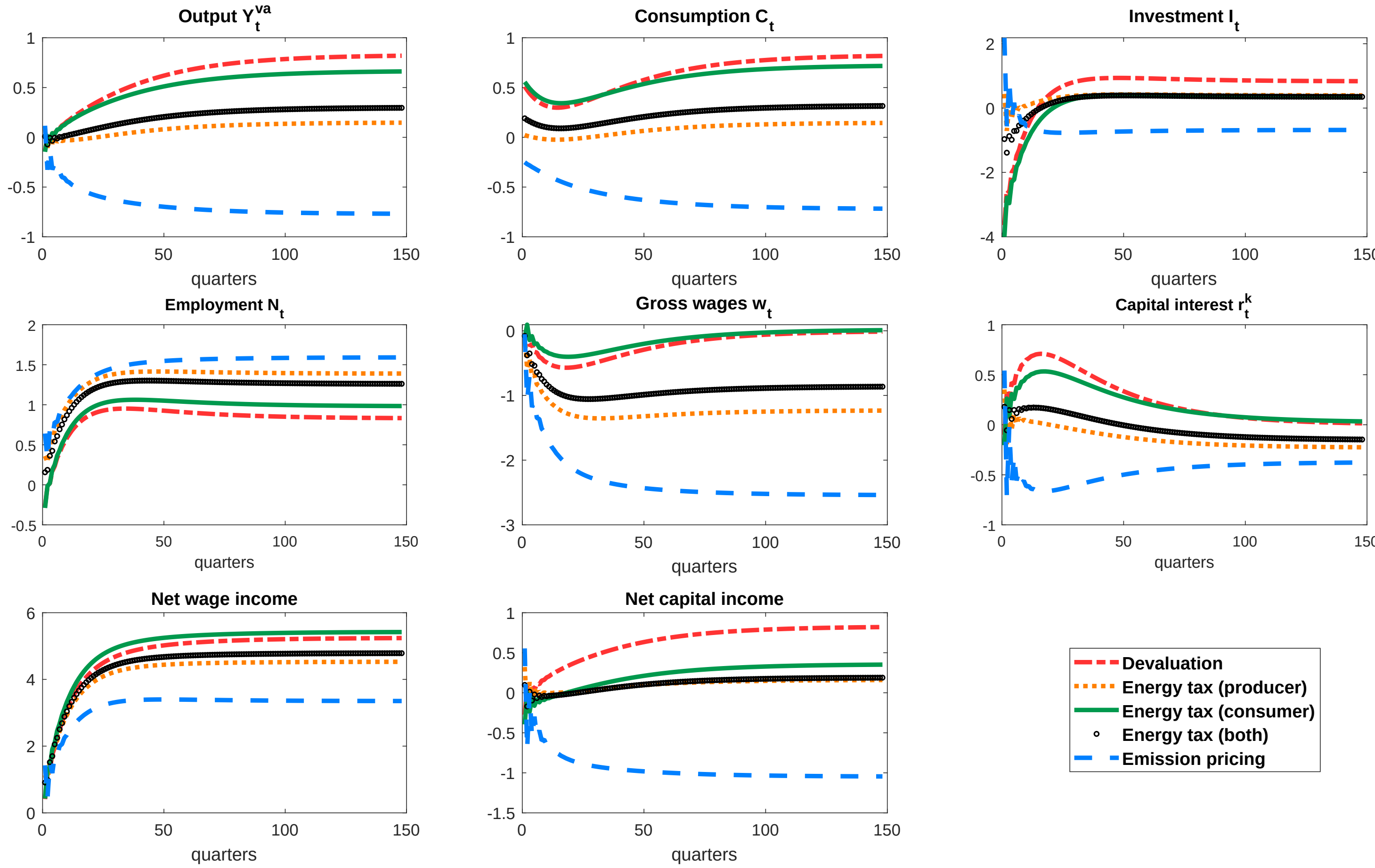
$$E_t \sum_{j=0}^{\infty} (\beta \kappa_s^p)^j \cdot \frac{\lambda_{t+j}}{\lambda_t} \left[\frac{\tilde{P}_{s,t}(j)}{P_{s,t+j}} - \tilde{mc}_{s,t+j} \right] \cdot y_{s,t}(z),$$

where κ_s^p is the sector-specific Calvo parameter, subject to equation (14), which yields the standard Calvo pricing equations (remember that, in the flexible price case, $\kappa_s^p = 0$) in which, again, $\tilde{mc}_{s,t}$ are the relevant marginal costs; see also Calvo (1983). For the monetary policy, we assume that it follows a standard Taylor rule, $\hat{R}_{s,t} = \rho^R \cdot \hat{R}_{s,t-1} + \chi^\pi \cdot \hat{\pi}_{t-1}^{cpi}$, where the hat indicates deviations from steady state (or targets), $\rho^R \in (0,1)$ is an AR(1)-coefficient and $\chi^\pi > 1$ the reaction coefficient on inflation. We set the AR(1) coefficient in the Taylor rule to 0.9 and assume that the central bank adjusts the policy rate by more than one-for-one with inflation, determined by the parameter $\chi^\pi = 1.5$. The sector-specific price durations are set as in Bouakez et al. (2021) and translated into respective Calvo parameters κ_s^p, summarized in Table B.2.[13]

[12] With flexible prices, emissions taxation becomes the most positive measure (in terms of output) in quarter 117 after the reform. With staggered price setting, this happens in quarter 122.

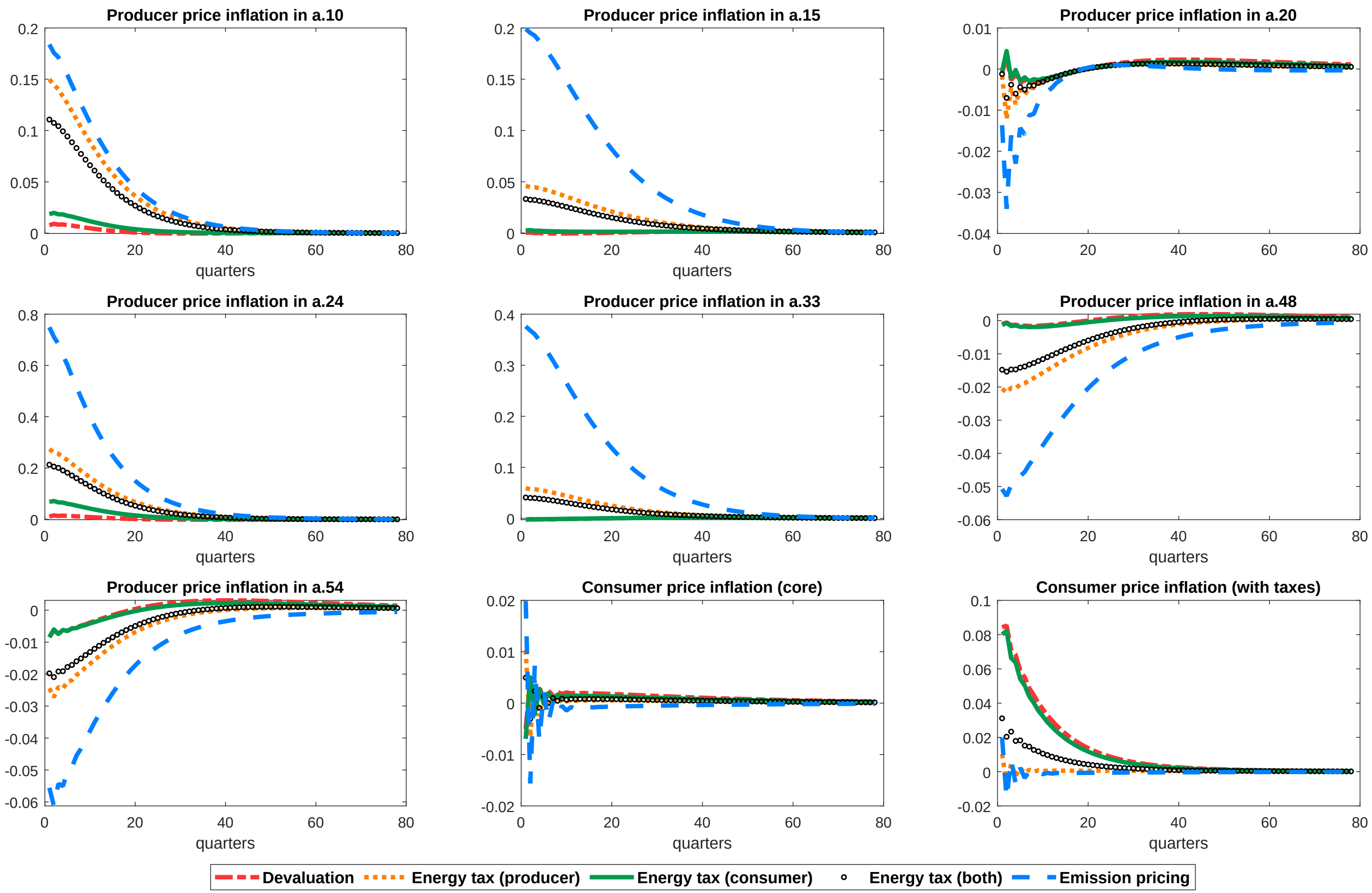
[13] We thank Hafedh Bouakez for sharing the price duration parameters with us. As price rigidities in sectors 10, 24 and 33-35 were extremely low, which caused implausible fluctuations, we increased these according to the values shown in the table.

Figure B.1: Implications of tax shift for key macroeconomic variables with staggered price setting (no damage)



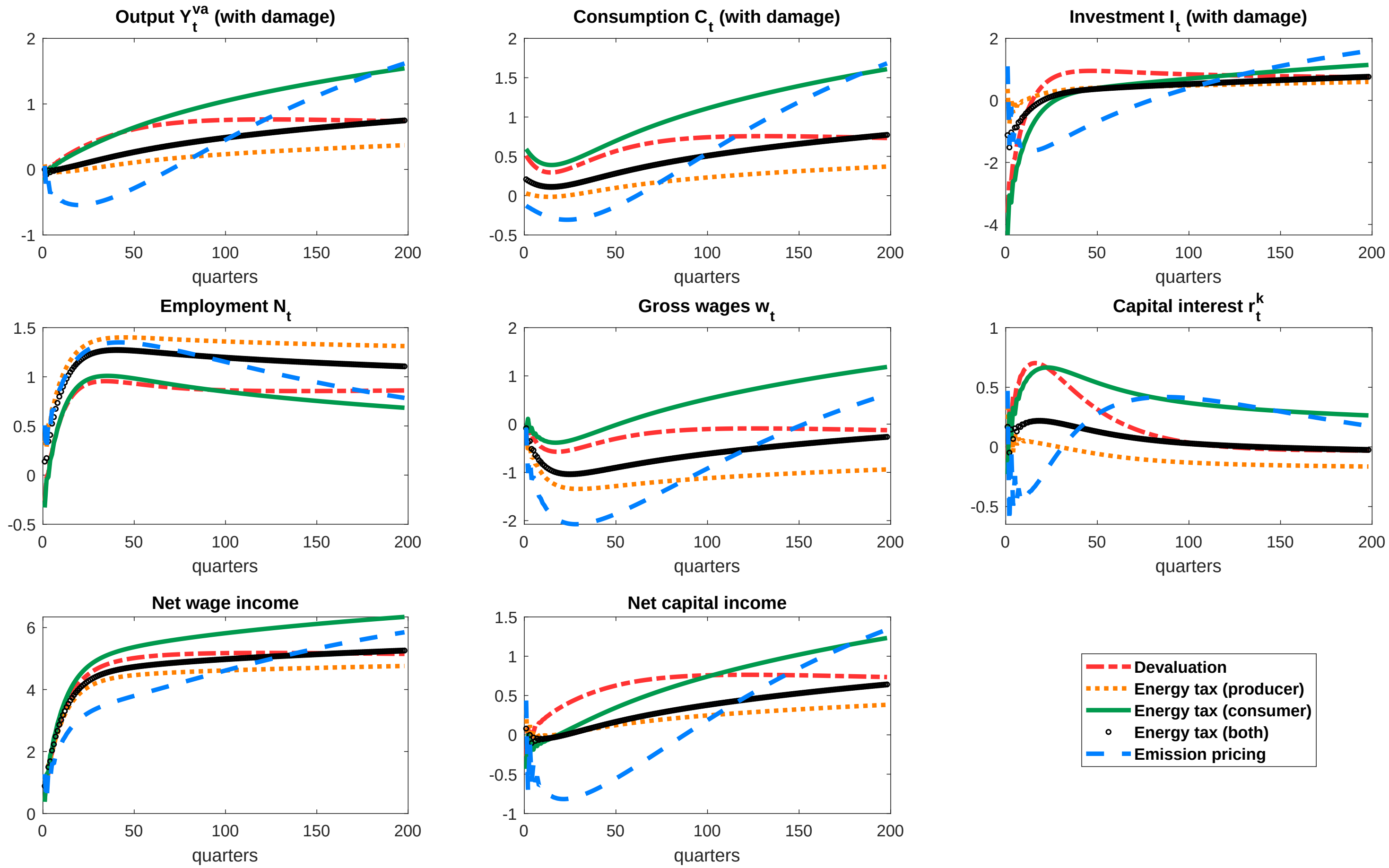
Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in percentage deviation (percentage point deviations for policy rate) from initial steady state, neglecting damage but taking into account staggered price setting. The red dotted-dashed line shows the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line.

Figure B.2: Implications of tax shift on prices for selected sectors (no damage)



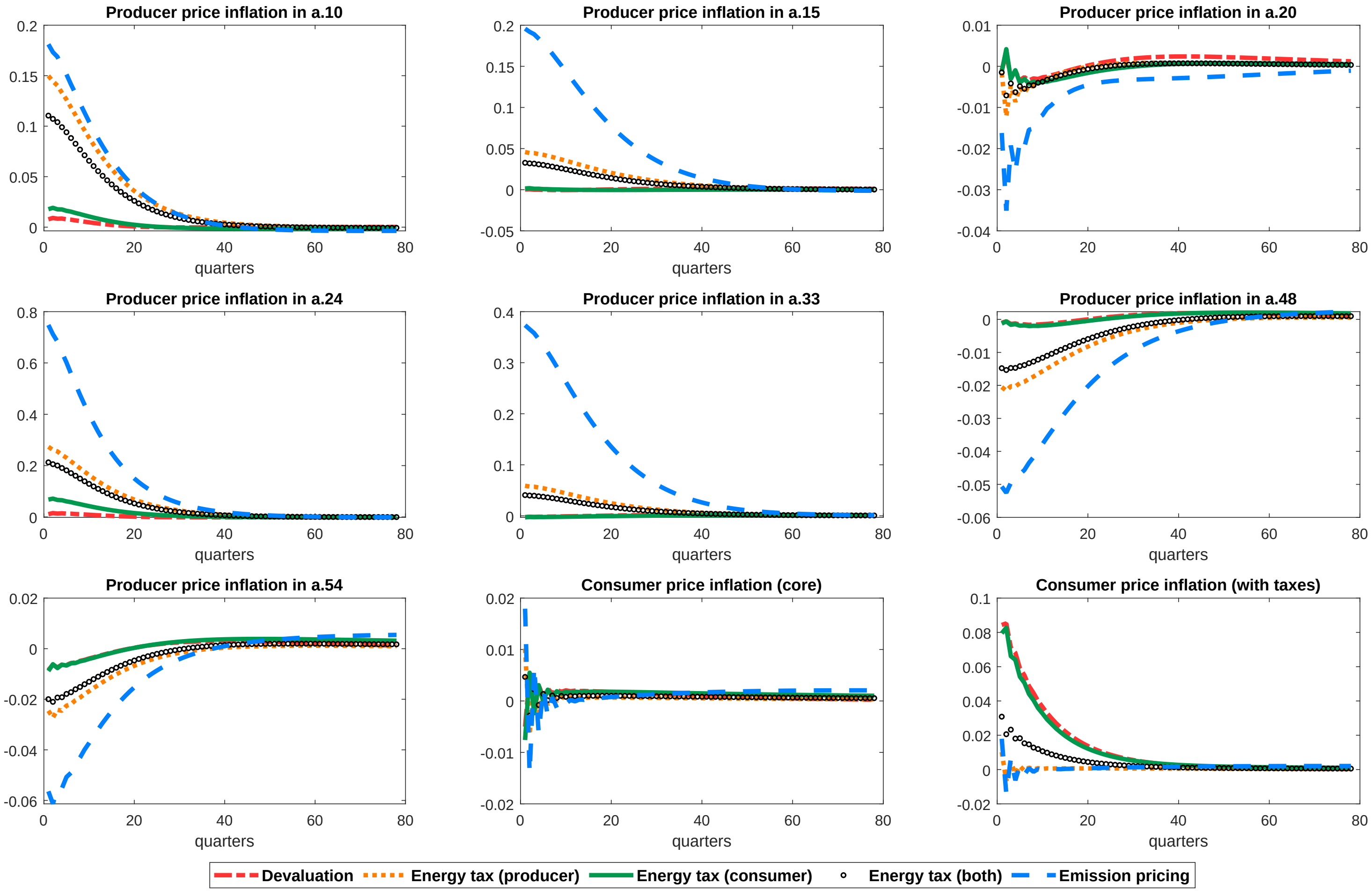
Notes: Figure plots (projected) implications of tax shifts for prices neglecting damage according to colored lines. CPI with taxes includes changes in τ_t^c.

Figure B.3: Implications of tax shift for key macroeconomic variables with staggered price setting (with damage)



Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in percentage deviation (percentage point deviations for policy rate) from initial steady state, taking into account damage and staggered price setting. The red dotted-dashed line shows the variables for conventional fiscal devaluation. Using energy taxation on the production side is depicted by the orange dotted line, the use of energy taxation on the consumption side by the green straight line, using both by the circled black line and the use of emission pricing by the dashed blue line.

Figure B.4: Implications of tax shift for prices of selected sectors (with damage)



Notes: Figure plots (projected) implications of tax shifts for prices with damage according to colored lines. CPI with taxes includes changes in τ_t^c.

Table B.1: Welfare effects under staggered price setting

Financing instrument:	$\tau^{c}_{s,t}$	$\tau^{Ep}_{10,24,t}$	$\tau^{Ec}_{10,24,t}$	$\tau^{Ep}_{10,24,t}$=$\tau^{Ec}_{10,24,t}$	P^{em}_{t}
Welfare with transition and flexible prices (from main text)					
Con. equiv. (no damage)	0.46	-0.20	0.38	-0.02	-0.93
Con. equiv. (with damage)	0.41	-0.05	0.90	0.26	0.49
Welfare with transition and staggered price setting					
Con. equiv. (no damage)	0.46	-0.21	0.38	-0.03	-0.95
Con. equiv. (with damage)	0.41	-0.06	0.91	0.25	0.46

Notes: Table shows welfare implications of different tax shifts, expressed in consumption-equivalent gain for the representative household in line with Lucas (2003), in percentage deviations from initial steady state.

Table B.2: Sector-specific price rigidities

	κ^{P}_{s}
1) Crop and animal production, hunting and related service activities	0.350
2) Forestry and logging	0.670
3) Fishing and aquaculture	0.670
4) Mining and quarrying	0.410
5) Manufacture of food products, beverages and tobacco products	0.660
6) Manufacture of textiles, wearing apparel and leather products	0.890
7) Manufacture of wood and of products of wood and cork, except furniture; MF of articles of straw and plaiting materials	0.790
8) Manufacture of paper and paper products	0.790
9) Printing and reproduction of recorded media	0.790
10) Manufacture of coke and refined petroleum products	0.800
11) Manufacture of chemicals and chemical products	0.760
12) Manufacture of basic pharmaceutical products and pharmaceutical prep.	0.760
13) Manufacture of rubber and plastic products	0.800
14) Manufacture of other non-metallic mineral products	0.570
15) Manufacture of basic metals	0.890
16) Manufacture of fabricated metal products, except machinery and equipm.	0.910
17) Manufacture of computer, electronic and optical products	0.760
18) Manufacture of electrical equipment	0.790
19) Manufacture of machinery and equipment n.e.c.	0.860

continued on next page

	κ_s^P
20) Manufacture of motor vehicles, trailers and semi-trailers	0.670
21) Manufacture of other transport equipment	0.690
22) Manufacture of furniture; other manufacturing	0.840
23) Repair and installation of machinery and equipment	0.880
24) Electricity, gas, steam and air conditioning supply	0.800
25) Water collection, treatment and supply	0.900
26) Sewerage; waste collection, treatment and disposal activities materials recov.; remediation act. & other waste managem. serv.	0.900
27) Construction	0.800
28) Wholesale and retail trade and repair of motor vehicles and motorcyc.	0.700
29) Wholesale trade, except of motor vehicles and motorcycles	0.880
30) Retail trade, except of motor vehicles and motorcycles	0.740
31) Land transport and transport via pipelines	0.610
32) Water transport	0.640
33) Air transport	0.900
34) Warehousing and support activities for transportation	0.900
35) Postal and courier activities	0.900
36) Accommodation and food service activities	0.510
37) Publishing activities	0.290
38) Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting act.	0.570
39) Telecommunications	0.940
40) Computer programming, consultancy and related activities; information service activities	0.900
41) Financial service activities, except insurance and pension funding	0.910
42) Insurance, reinsurance and pension funding, except compulsory social security	0.910
43) Activities auxiliary to financial services and insurance activities	0.910
44) Real estate activities	0.910
45) Legal and accounting activities; activities of head offices; management consultancy activities	0.870
46) Architectural and engineering activities; technical testing and analysis	0.900
47) Scientific research and development	0.900
48) Advertising and market research	0.900
49) Other professional, scientific and technical activities; veterinary act.	0.900
50) Administrative and support service activities	0.780
51) Public administration and defence; compulsory social security	0.710
52) Education	0.710
53) Human health and social work activities	0.840
54) Other service activities	0.870

Notes: The table shows calibrated values for sector-specific price rigidities.

Appendix C: Comparison with a one-sector economy

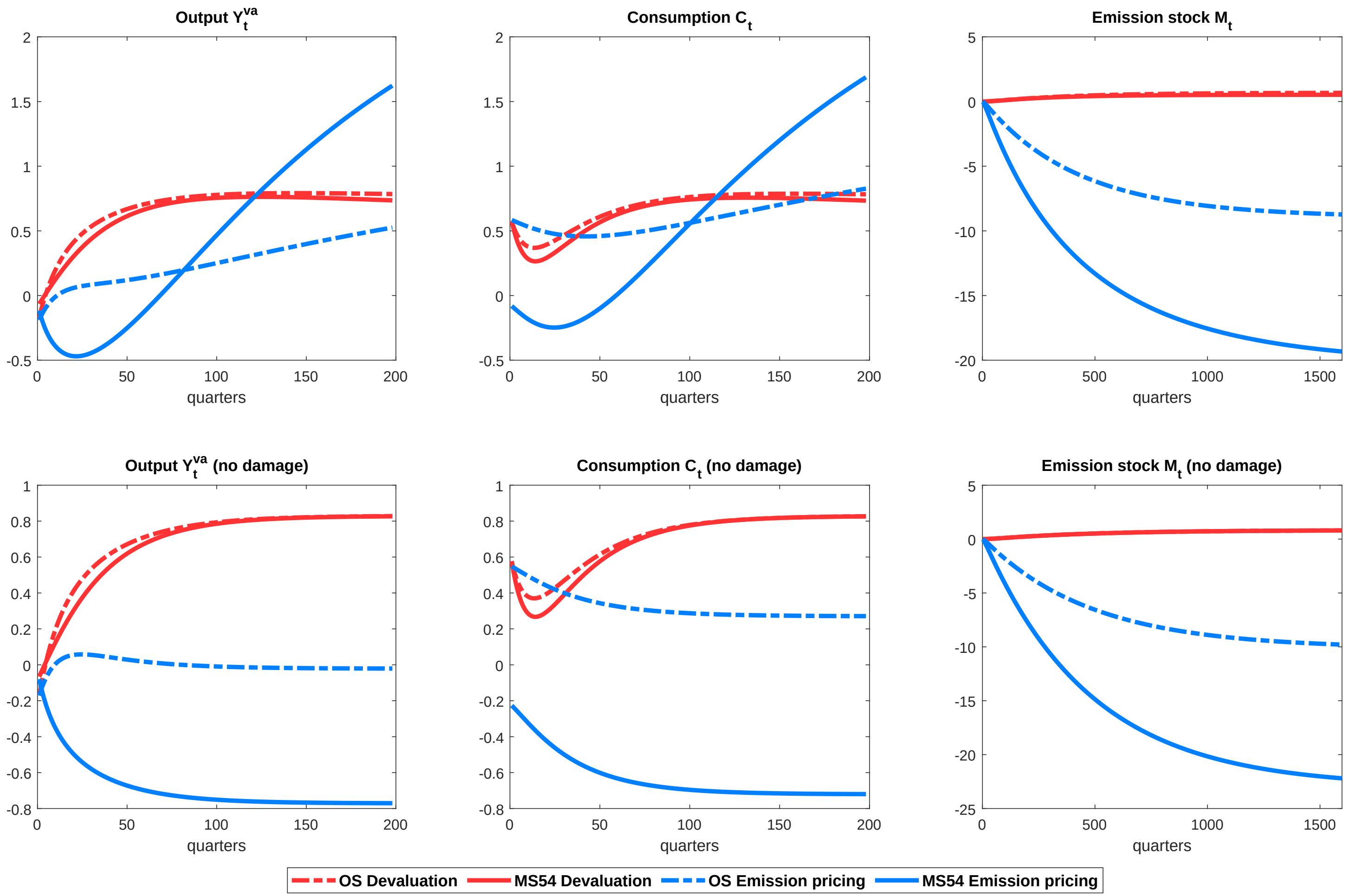
In this appendix, we show the simulation results of the above experiments in a one-sector economy model and compare those to the multi-sector economy of the main text. The one-sector economy is calibrated to quarterly frequency. Emission intensity is chosen to match the average emission intensity of the multi-sector model. The same holds for labor intensity, capital intensity and factor inputs. Hence, also the one-sector model contains roundabout production. Results of simulating fiscal devaluation and financing the labor tax cut by emission pricing are summarized in Figure C.1.

Comparing the results, we see that there is basically no difference between the one and the multi-sector economy when simulating fiscal devaluation. The reason is that, in this case, consumption costs increase analogously for any sectoral good and, thereby, hamper demand for these goods more or less equally. The same is true for the tax-induced labor cost reduction (with opposite sign, of course). Hence, whether fiscal devaluation happens in a one or a more-sector economy does not seem to play a major role.

When the labor tax reduction is financed by an increase in emission pricing, however, having a multi-sector economy plays a role. Even though marginal costs increase in all sectors, they do so more in sectors which are emissions-intensive (see also discussion in the previous Appendix B). These sectors become less competitive which shifts away demand from sectors that are emissions-intensive towards sectors that are not. Some sectors even benefit from the reform, which is especially true in the case emissions cause economic damage (see also Figures 3 and 4). In the one-sector economy, economic agents have no chance to shift demand and, therefore, output and consumption losses in the one-sector economy are higher. Assuming that labor and capital can be shifted between sectors relatively easily, as we did in the multi-sector economy by setting the corresponding parameters accordingly (see Section 4 for a discussion), fosters this finding. If substitutability falls, the beneficial effects in the multi-sector economy (in relative terms) also decrease.

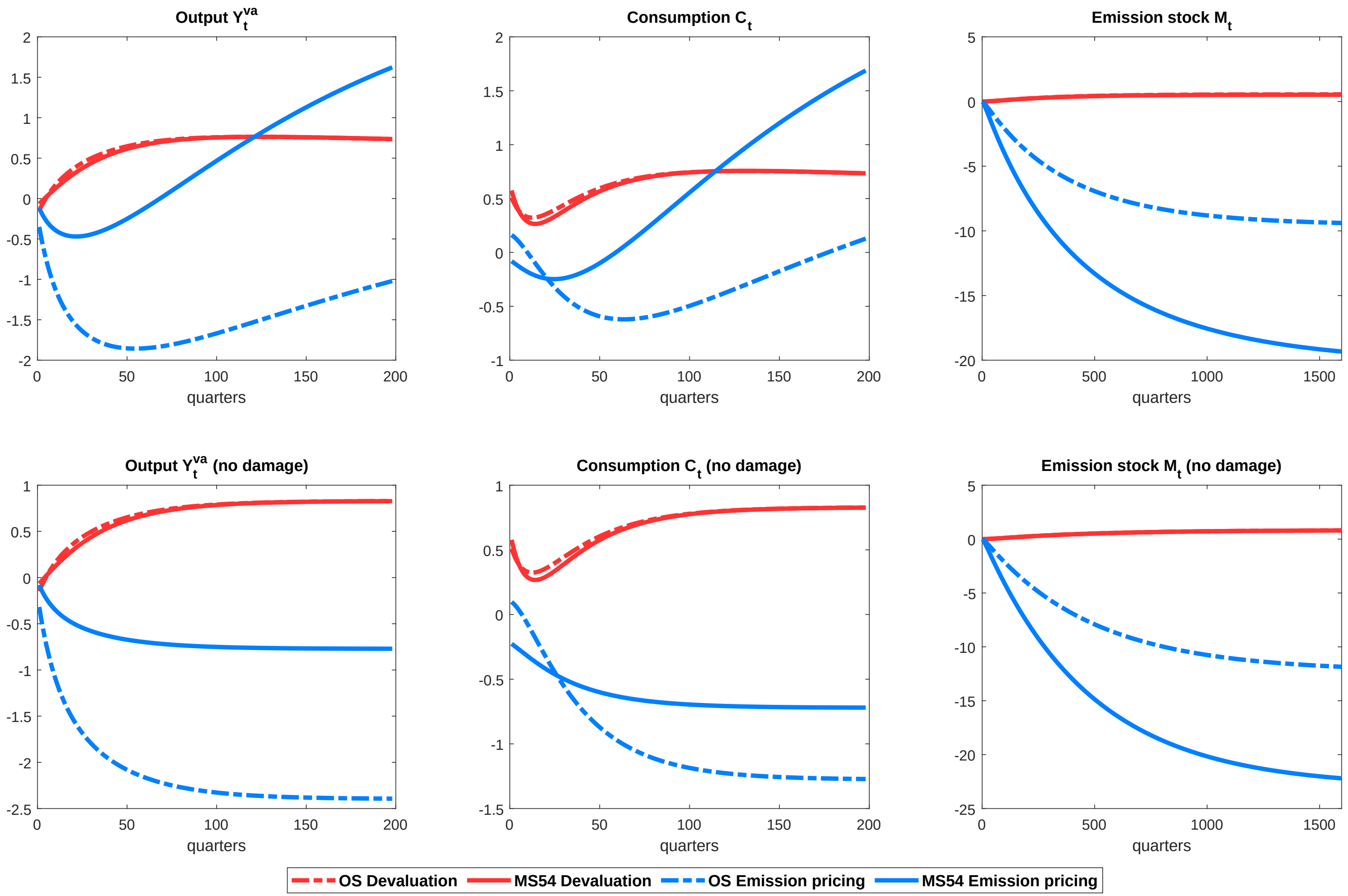
In case we assume no roundabout production (i.e. we assume only labor and capital and no intermediate goods to be production inputs, which we approximate by setting $\alpha_{H,s} = 0.9999$), the opposite is true (see Figure C.2). Because firms can no longer shift demand for intermediate inputs from relatively more expensive to cheaper goods, relative production costs increase more in the one-sector economy and output is affected more negatively. With roundabout production, the multi-sector economy allows to dampen this production cost increase through the shift in demand for production inputs. If there is emission damage, this is also true, at least on impact and for some time thereafter. As emissions and damage fall, the positive productivity effects outweigh the cost increase, as described in the main text.

Figure C.1: Comparing simulation results in a one and a multi-sector economy



Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in a model of a one-sector economy and of our benchmark model with the multi-sector economy (presented in the main text).

Figure C.2: Comparing simulation results in a one and a multi-sector economy without roundabout production



Notes: Figure plots (projected) implications of tax shifts for key macroeconomic variables in a model of a one-sector economy and of our benchmark model with the multi-sector economy (presented in the main text) when assuming that there is no roundabout production.