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Ulrich Eydam
Francesca Diluiso

Center for Economic Policy Analysis

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University of Potsdam
August-Bebel-Straße 89, 14482 Potsdam
Tel.: +49 331 977-3225
Fax: +49 331 977-3210
E-Mail: dp-cepa@uni-potsdam.de

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**How to Redistribute the Revenues from Climate Policy? A Dynamic Perspective with Financially Constrained Households***

**Ulrich Eydam**
University of Potsdam

**Francesca Diluiso**
Mercator Research Institute on Global Commons and Climate Change (MCC)

ABSTRACT

In light of climate change mitigation efforts, revenues from climate policies are growing, with no consensus yet on how they should be used. Potential efficiency gains from reducing distortionary taxes and the distributional implications of different revenue recycling schemes are currently debated. To account for households heterogeneity and dynamic trade-offs, we study the macroeconomic and welfare performance of different revenue recycling schemes using an Environmental Two-Agent New-Keynesian model, calibrated on the German economy. We find that, in the long run, welfare gains are higher when revenues are used to reduce distortionary taxes on capital, but this comes at the cost of higher inequality: while all households prefer labor income tax reductions to lump-sum transfers, only financially unconstrained households are better off when reducing taxes on capital income. Interestingly, we find that over the transition period relevant to meet short-medium run climate targets, labor income tax cuts are the most efficient and equitable instrument.

**Keywords:** double dividend, E-DSGE, environmental tax reform, non-Ricardian households, revenue recycling
**JEL Codes:** E62, H23, H31, Q58

**Corresponding author:**
Ulrich Eydam
University of Potsdam
Faculty of Economics and Social Sciences
August-Bebel-Straße 89
14482 Potsdam
Germany
E-mail: ulrich.eydam@uni-potsdam.de

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# 1 Introduction

Efforts to reduce carbon emissions and contrast global warming are becoming more pressing and several policy options are currently being debated. Carbon pricing is largely recognized by economists as the most efficient tool to address negative externalities from emissions and to achieve a cost-effective transition to a low-carbon economy (see e.g. Stiglitz et al., 2017). It engages the private sector in abatement efforts, reduces the demand for carbon-intensive goods, and generates public revenues. Nevertheless, in practice, gaining political support for pricing carbon is a challenge for policy makers. General aversion for additional tax burden and concerns about the potentially regressive effects of carbon pricing (see e.g. Ohlendorf et al., 2021) are primary obstacles for the implementation of this policy, together with social-psychological and contextual factors that influence public opinion and climate change perception (see e.g. Drews and Van den Bergh, 2016; Levi, 2021).

A large body of literature has focused on how to enhance the public support for carbon pricing through an appropriate use of the revenues raised, analyzing different recycling schemes from an acceptability, equity, and efficiency perspective (Klenert et al., 2018). Revenues from climate policy can be used to finance direct transfers to citizens, reduce other taxes, or subsidize specific investments into green technologies. Previous literature in the domain of public finance has particularly emphasized the potential double dividend arising from environmental policies when other distortionary taxes are reduced: one dividend comes from the improvement in environmental conditions and a second one from the reduction of the overall economic costs and distortions associated with the pre-existing tax system. The strong form of double dividend asserts that a green tax reform would be welfare enhancing, even without considering the welfare associated with improvement in environmental conditions. The weak double dividend argument, instead, states that, when revenues from carbon taxes are used to reduce other pre-existing taxes, the welfare improvement must be greater than the welfare improvement from a reform where the environmental taxes are returned in a lump-sum fashion (see e.g. Goulder, 1995; Bovenberg, 1999).[1] Since most of the double dividend literature abstracts from households heterogeneity, concerns about equity and distributional aspects have largely been overlooked. However, given that the instrument chosen to rebate revenues exerts heterogeneous effects across income groups, taking the distributional effects into account can be relevant for the assessment of the overall welfare implications.

From a policy perspective, considering that the revenues from climate policy will constitute a

[1] One strand of literature on the double dividend focuses on optimal tax structure and the level of environmental taxes in the presence of pre-existing distortions (e.g. Bovenberg and De Mooij, 1994; Bovenberg and Goulder, 1996). Another strand of contributions adopt a positive approach and assesses the impacts of specific policy reforms when interaction effects between different fiscal levies are in place. See Goulder (1995); Jorgenson and Wilcoxen (1993); Goulder and Hafstead (2013) among the others. This paper pertains to this second strand of literature and abstracts from optimal policy considerations.

substantial share of the government budget in the next future, it is important to understand how these revenues should be used taking into account both efficiency and distributional aspects. We chose Germany as a case study. The country has recently set new ambitious climate targets to reach a 65% emissions reduction by 2030 compared to 1990 levels and carbon neutrality in 2045. Recent literature focusing on redistribution of climate revenues in this country points in different directions. Edenhofer et al. (2019) argue that a per capita refund for households (climate dividend) would make climate policy more socially balanced and find that about 67% of households would benefit from a 'carbon tax cum dividend'. Van der Ploeg et al. (2021) use household data on income, consumption, labor supply, and carbon footprints to empirically investigate the effects of different recycling options. They find that if the revenues from a carbon tax are recycled via lump-sum transfers to all households, 70% of households are worse off, due to increases in consumer prices, negative effects on the labor markets and erosion of income tax base. Vice versa, lowering income taxes proves to be beneficial for about 50% of households, resulting in higher efficiency but at the expense of more inequality.

We contribute to this debate providing a modeling perspective. We build an Environmental Two-Agent New Keynesian model (E-TANK), featuring financially constrained and financially unconstrained households. We introduce a carbon tax, calibrated to meet the German climate targets, and study the performance of different recycling schemes. Climate policy revenues can be redistributed via lump-sum transfers, used to increase public spending, or used to reduce taxes on capital gain or labor income.

Our contribution to the literature is threefold. First, we analyze the macroeconomic and welfare effects of these policies in a set-up involving several frictions usually disregarded in studies on double dividend. These features are relevant to capture the behavior of the economy in the short and medium run.[2] Second, while most of the double dividend literature focuses on static settings and long-run outputs[3]and abstracts from uncertainty, we provide an analysis adopting both a stochastic and a deterministic perspective. In a stochastic environment we study the response of the economy to business cycle shocks under different recycling regimes and the long run aggregate macroeconomic and welfare effects of these policies when business cycle uncertainty is factored in. We then adopt a deterministic perspective and disentangle the effects exclusively due to the implementation of the carbon tax at different time horizons and for different recycling schemes over a ten-year mitigation period. Third, by introducing non-Ricardian households in the model, we are able to capture not only the efficiency gains of different policies but also their distributional impacts, usually disregarded in

[2]Studies adopting a general equilibrium framework to account for potential interactions between carbon taxes and other fiscal instruments usually do not include monopolistic competitions, investment adjustment costs, and price rigidities. See Glomm et al. (2008) and Barrage (2020) among the others.

[3]See e.g. Barrage (2020) for a discussion on these points.

representative agent models.[4]

Methodologically the paper pertains to a recent strand of literature using New Keynesian models to study the impact of environmental regulation on macroeconomic aggregates in the presence of different types of shocks (see e.g. Annicchiarico and Di Dio, 2015; Annicchiarico and Diluiso, 2019).[5] In this literature landscape only few papers explicitly analyze the implications of the redistribution of revenues from climate policy. Annicchiarico et al. (2018) build a New Keynesian model with oligopolistic firms and analyze recycling options along a deterministic mitigation path. They find that using carbon revenues to reduce consumption or labor taxes is less harmful for the economy than recycling through lump-sum transfers and that major differences materialize in the medium-long run, in particular when revenues are used to reduce labor income taxes. Finally, they show how the efficiency gains of recycling are larger in oligopoly than in perfect competition. Jaimes (2021) studies the reaction of the economy to an abatement cost shock and finds that when environmental policy revenues are used to reduce existing distortionary taxes on consumption or labor the negative effects of this type of shock are dampened. Finally, Eydam (2021) compares the distributional implications of different climate policy instruments. While the analysis abstracts from distortionary types of taxation, it generally highlights that revenue recycling schemes are important for the distributional effects of climate policies. To the best of our knowledge, a comprehensive analysis combining both a stochastic and deterministic perspective to capture the trade-off between efficiency and equity in the redistribution of climate policy revenues is still missing. This paper provides a first attempt in this direction.

We find that in the long run using climate policy revenues to reduce distortionary taxes is preferable from a welfare perspective compared to a redistribution via lump-sum transfers. However, when considering distributional effects, reductions in capital income taxes are only favorable for Ricardian households, while labor tax reductions are preferable for both types of households. If higher degrees of inequality aversion are factored in, or if we consider only the transition period to reach medium terms climate targets, reducing labor taxes becomes not only the most equitable choice, but also the most efficient.

The remainder of the paper is organized as follows. Section 2 describes the model, section 3 details the calibration strategy, section 4 presents and discusses the results, and section 5 provides some concluding remarks.

[4] A notable exception deviating from the assumption of representative households is provided by Fried et al. (2021) which study the welfare implications of a broad set of revenue recycling options in an overlapping generation model where agents are heterogeneous in several dimensions.

[5] For a survey of the literature on environmental DSGE models see Annicchiarico et al. (2021).

# 2 Model

## 2.1 Model Structure

We integrate carbon dioxide emissions and climate policy into a standard New Keynesian DSGE model. We model emissions as a by-product of a polluting intermediate input (e.g. Fischer and Springborn, 2011) and we assume public authorities can charge a carbon tax per unit of emissions. Emissions increases the stock of pollution in the atmosphere that negatively impacts the productivity of the economy. We model the negative externality due to climate change as in Golosov et al. (2014). Following Galí et al. (2007) we distinguish between financially unconstrained (Ricardian households) and financially constraint households (non-Ricardian households). Ricardian households own good-producing firms and possess the stock of physical capital, while non-Ricardian households have no access to capital markets. As common in the literature we introduce real and nominal rigidities: we assume that investment is subject to convex adjustment costs (e.g. Christiano et al., 2005), and good-producing firms operate under monopolistic competition and face nominal price setting frictions as in Calvo (1983).

Since the focus of the present analysis is on fiscal policy, we model a rich set of tax instruments. We assume the government levies value added taxes, labor income taxes, capital income taxes, and, carbon taxes. Furthermore, the government can issue one-period risk free bonds which are bought by Ricardian households. To balance the budget, the government conducts lump-sum taxes or transfers. Monetary policy is conducted by a central bank via a standard Taylor rule.

## 2.2 Households

The economy is populated by a continuum of households $I \in [0,1]$. In particular, we assume that two types of households exist as in Galí et al. (2004). A fraction $1-\lambda$ of households has access to capital markets, can accumulate physical capital $k_t$ and rent it to firms. We refer to these households as Ricardian households and we label them with the subscript $R$. The remaining fraction of households, $\lambda$, has no access to capital markets and owns no assets. These households will be referred to as non-Ricardian households with subscript $N$.

*Ricardian Households*

The representative Ricardian household chooses consumption $c_{R,t}$, investment $x_t$ and labor hours

$h_{R,t}$ to maximize its expected life-time utility:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{c_{R,t}^{1-\rho}}{1-\rho} - \psi_R \frac{h_{R,t}^{1+\chi}}{1+\chi} \right], \tag{1}$$

where $\beta \in (0,1)$ denotes the discount factor of households, $\psi_R$ denotes the disutility from labor of Ricardian households, $\chi > 0$ denotes the inverse of the Frisch elasticity and $\rho$ denotes the inverse of the intertemporal elasticity of substitution. Ricardian households face the following flow budget constraint:

$$(1+\tau_c)c_{R,t} + x_t + b_t = (1-\tau_L)w_t h_{R,t} + R_{t-1}\frac{b_{t-1}}{\Pi_t} + (1-\tau_k)F_t + (1-\tau_k)r_{k,t}k_t + T_t, \tag{2}$$

where $w_t$ denotes the real wage, $r_{k,t}$ is the real return of capital, $\Pi_t = \frac{p_t}{p_{t-1}}$ denotes inflation, $b_t$ denotes the stock of one period risk-free government bonds, $R_t$ denotes the nominal interest rate, $F_t$ are firm profits distributed lump-sum to Ricardian households, and $T_t$ denotes lump-sum transfers. The value added tax rate is denoted by $\tau_c$, the labor income tax rate by $\tau_L$, and the capital income tax rate by $\tau_k$.

In order to capture the fact that capital cannot be adjusted instantaneously at business cycle frequencies, convex investment adjustment costs, similar to Christiano et al. (2005), are introduced as follows:

$$k_{t+1} = \left[ 1 - \frac{\kappa}{2}\left( \frac{x_t}{x_{t-1}} - 1 \right)^2 \right] x_t + (1-\delta)k_t. \tag{3}$$

Here, $\kappa$ captures the degree of adjustment costs and $\delta$ denotes the depreciation rate of capital. With this formulation, the costs of investment increase in the growth rate of investment. Thus, large increases in investment in a single period are particularly expensive, which implies that households will spread investment over several periods. Therefore, adjustments of the stock of physical capital require time.

The solution of the household problem yields the following first-order conditions for consumption, labor supply, bond holding, investment, and capital:

$$\lambda_{R,t} = c_{R,t}^{-\rho}(1+\tau_c)^{-1}, \tag{4}$$

$$\psi_R h_{R,t}^{\chi} = \frac{(1-\tau_L)}{(1+\tau_c)} c_{R,t}^{-\rho} w_t, \tag{5}$$

$$\lambda_{R,t} = \beta R_t E_t \lambda_{R,t+1} \Pi_{t+1}^{-1}, \tag{6}$$

$$1 = q_t \left[1 - \frac{\kappa}{2}\left(\frac{x_t}{x_{t+1}} - 1\right)^2 - \kappa\left(\frac{x_t}{x_{t-1}} - 1\right)\frac{x_t}{x_{t-1}}\right] + \beta E_t \frac{\lambda_{R,t+1}}{\lambda_{R,t}} q_{t+1}\kappa\left(\frac{x_{t+1}}{x_t} - 1\right)\left(\frac{x_{t+1}}{x_t}\right)^2, \quad (7)$$

$$q_t = \beta E_t \frac{\lambda_{R,t+1}}{\lambda_{R,t}}\left[(1-\delta)q_{t+1} + (1-\tau_k)R_{K,t+1}\right], \quad (8)$$

where $\lambda_{R,t}$ denotes the marginal utility of an additional unit of consumption and $q_t$ denotes the Tobin's q, which captures the value of installed capital relative to new capital.

*Non-Ricardian Households*

Non-Ricardian households cannot smooth consumption through saving and thus seek to optimize their utility period-by-period. In the following, we assume that the utility function is additive-separable and has the functional form: $u_N = \frac{c_{N,t}^{1-\rho}}{1-\rho} - \psi_N \frac{h_{N,t}^{1+\chi}}{(1+\chi)}$. In the absence of access to capital markets, non-Ricardian households face a constraint, which restricts their consumption $c_{N,t}$ to their current income, i.e. $(1+\tau_c)c_{N,t} = (1-\tau_L)w_t h_{N,t} + T_t$. The labor supply of non-Ricardian households $h_{N,t}$ is given by:

$$h_{N,t}^{\chi} = \frac{(1-\tau_L)}{\psi_N(1+\tau_c)} c_{N,t}^{-\rho} w_t, \quad (9)$$

which in this case is not constant and depends on the real wage and the marginal utility from consumption.

## 2.3 Firms

The production sector of the economy can be divided into two layers. Final goods producers operate under perfect competition and aggregate intermediate goods into a final output $y_t$. The intermediate goods $y_{j,t}$ are produced by a continuum of intermediate firms $j \in [0,1]$ operating under monopolistic competition. Intermediate firms face nominal price rigidities. For production intermediate firms rely on capital, labor and a polluting intermediate input factor $m_{j,t}$. For simplicity, we assume that they buy the polluting intermediate factor on international markets and normalize its price to one.

Final goods producers use a CES aggregator of the form $y_t = (\int_0^1 y_{j,t}^{(\varepsilon-1)/\varepsilon} dj)^{\varepsilon/(\varepsilon-1)}$ to combine intermediate goods into final goods. Here $\varepsilon > 1$ denotes the elasticity of substitution between different varieties of intermediate goods. Profit maximization of final goods producers yields the usual downward sloping demand for intermediate goods $y_{j,t} = (\frac{p_{j,t}}{p_t})^{-\varepsilon} y_t$. The demand for the intermediate good $j$ is a decreasing function of the individual price of the intermediate good $p_{j,t}$ relative to the overall price level of the economy $p_t$. Using the demand for individual goods, the price level of the economy, defined as the sum over intermediate prices times quantities, is $p_t = (\int_0^1 p_{j,t}^{1-\varepsilon} dj)^{1/(1-\varepsilon)}$.

Intermediate good firms produce according to the following constant returns to scale technology:

$$y_{j,t} = (1-d(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma}, \qquad 0<\alpha<1, \qquad 0<\gamma<1, \tag{10}$$

where $A_t$ represents total factor productivity (TFP) which evolves as $A_t = \rho_a A_{t-1} + \varepsilon_{a,t}$. Here $\rho_a$ denotes the autocorrelation of the AR(1) process and $\varepsilon_{a,t}$ denotes the innovations in productivity that are assumed to be i.i.d. normally distributed. The output elasticity with respect to the polluting intermediate input is denoted by $\gamma$ and $\alpha$ denotes the output elasticity of physical capital. We assume that emissions $e_{j,t}$ are equal to the utilization of the polluting intermediate input and that the government imposes an emission tax $\tau_E$ per unit of emission.

Production losses from climate change are introduced via a damage function and depend on the stock of greenhouse gases in the atmosphere. Following Golosov et al. (2014) we adopt the following simplified specification for the damage function:

$$(1-d(s_t)) = exp(-\eta_s(s_t - \bar{s})), \tag{11}$$

where $\eta_s$ is a scale parameter, $\bar{s}$ denotes the pre-industrial level of atmospheric greenhouse gases and $s_t$ is the pollution stock in the atmosphere evolving as:

$$s_t - \bar{s} = (1-\delta_s)(s_{t-1} - \bar{s}) + e_t + e_t^w, \tag{12}$$

where $\delta_s$ is the decay rate of greenhouse gases and $e_t^w$ denotes emissions from the rest of the world.

Intermediate firms take factor prices as given, so that their static cost minimization problem yields the following optimality conditions for factor inputs:

$$r_{k,t} = \lambda_{j,t}\alpha(1-d(s_t))A_t k_{j,t}^{\alpha-1} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma}, \tag{13}$$

$$w_t = \lambda_{j,t}(1-\alpha-\gamma)(1-d(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{-\alpha-\gamma} m_{j,t}^{\gamma}, \tag{14}$$

$$1+\tau_E = \lambda_{j,t}\gamma(1-d(s_t))A_t k_{j,t}^{\alpha} h_{j,t}^{1-\alpha-\gamma} m_{j,t}^{\gamma-1}. \tag{15}$$

Here, the Lagrange multiplier $\lambda_{j,t} = mc_{j,t}$ can be interpreted as the marginal cost of the firm, i.e. the cost of producing an additional unit of output. From (15) we can infer that at the optimum, firms choose the amount of the polluting intermediate input, such that marginal revenues equate marginal costs. This implies that regulatory measures that increase the cost of employing intermediate inputs, will distort the choice of input factors and incentivize firms to reduce emissions. Furthermore, conditions (13) - (15) imply that all firms will choose the same capital-labor and intermediate inputs-labor ratios so that marginal costs are common to all firms, i.e. $mc_{j,t} = mc_t$, where:

$$mc_t = \left(\frac{1}{1-\alpha-\gamma}\right)^{1-\alpha-\gamma}\left(\frac{1}{\alpha}\right)^{\alpha}\left(\frac{1}{\gamma}\right)^{\gamma}\frac{w_t^{1-\alpha-\gamma} r_{k,t}^{\alpha}(1+\tau_E)^{\gamma}}{((1-d(s_t))A_t)}. \tag{16}$$

Intermediate goods producers use their market power and choose the price of intermediate goods $p_{j,t}$ that maximizes discounted real profits. To this end, they apply the stochastic discount factor of Ricardian households defined as $\Lambda_{t,t+i} = \beta\frac{\lambda_{R,t+i}}{\lambda_{R,t}}$. Every period only a fraction $(1-\theta_p)$ of firms can adjust the prices. The firms that cannot adjust their prices remain at their previously chosen prices. The solution to this dynamic price-setting problem implies that all firms that can reset prices will choose the same optimal reset price $p_t^*$, given by:

$$p_t^* = p_{j,t} = \frac{\varepsilon}{(\varepsilon-1)}\frac{E_t\sum_{i=0}^{\infty}\theta_p^i\Lambda_{t,t+i}p_{t+i}^{\varepsilon}y_{t+i}mc_{t+i}}{E_t\sum_{i=0}^{\infty}\theta_p^i\Lambda_{t,t+i}p_{t+i}^{\varepsilon-1}y_{t+i}}. \tag{17}$$

With $\theta_p = 0$, all firms can freely adjust their prices and the price of intermediate goods will be a markup $\frac{\varepsilon}{(\varepsilon-1)} > 1$ over marginal costs. With $\theta_p > 0$, the evolution of the aggregate price level is given by $p_t = [(1-\theta_p)p_t^{*1-\varepsilon} + \theta_p p_{t-1}^{1-\varepsilon}]^{1/(1-\varepsilon)}$, which implies that the current aggregate price level corresponds to the weighted average of recently adjusted and previous prices. For later reference, we rewrite this in terms of inflation as $1 = (1-\theta_p)\Pi_t^{*1-\varepsilon} + \theta_p\Pi_t^{\varepsilon-1}$, where $\Pi_t = \frac{p_t}{p_{t-1}}$ and $\Pi_t^* = \frac{p_t^*}{p_t}$. The profits of firms $F_t$ are distributed lump-sum to Ricardian households.

## 2.4 Public sector and market clearing

*Central Bank*

The short-term gross nominal interest rate $R_t$ is set by a central bank, which has the objective to maintain price stability and reacts to deviations of inflation from the inflation target $\bar{\Pi}$. Monetary policy is conducted according to following policy rule:

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\gamma_R}\left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\gamma_\Pi(1-\gamma_R)} exp(\varepsilon_{R,t}). \tag{18}$$

Here, $\gamma_\Pi$ denotes the coefficient that captures the reaction of the central bank to deviations of inflation from the target and $\gamma_R$ captures the persistence in nominal interest rates, which ensures empirically plausible smooth adjustments in nominal rates. $\bar{R}$ denotes the steady state nominal interest rate and $\varepsilon_{R,t}$ denotes stochastic innovations in the nominal rate.

*Government*

We assume that government spending $g_t$ is unproductive and financed via different types of non-distortionary and distortionary taxes. The government provides lump-sum transfers $T_t$ to both types of households. The flow budget constraint of the government is given by:

$$g_t + R_{t-1}b_{t-1}/\Pi_t = b_t - T_t + \tau_L w_t h_t + \tau_k(r_{k,t}k_t + F_t) + \tau_c c_t + \tau_E e_t. \tag{19}$$

i.e. real government expenditures are financed via issuing risk-free bonds $b_t$, through capital income taxes $\tau_k(r_{k,t}k_t + F_t)$, labor income taxes $\tau_L w_t h_t$, value added taxes $\tau_c c_t$ and through the revenues of the emission reduction scheme $\tau_E e_t$. To ensure the long-run sustainability of government debt, the government follows the fiscal rule:

$$T_t = \bar{T} - \phi_T(b_t - \bar{b}), \tag{20}$$

where $\bar{T}$ denotes steady state lump-sum transfer and $\phi_T$ captures the intensity of adjustments in transfers in response to deviations of the stock of government debt from the debt target $\bar{b}$. Government expenditures are stochastic and follow the AR(1) process $g_t = (1-\rho_g)\bar{g} + \rho_g g_{t-1} + \varepsilon_{g,t}$. Here, $\bar{g}$ denotes an exogenous target of government consumption and $\rho_g$ captures the persistence of i.i.d. innovations in government consumption denoted by $\varepsilon_{g,t}$.

*Aggregation*

In the competitive equilibrium of the model goods and factor markets clear. Factor markets clearing implies $k_t = \int_0^1 k_{j,t}\,dj$, $m_t = \int_0^1 m_{j,t}\,dj$ and $h_t = \int_0^1 h_{j,t}\,dj$. By assumption emissions are directly proportional to the utilization of polluting inputs, i.e. $e_t = m_t$. Given the demand for intermediate goods,we have $\int_0^1 y_{j,t}dj = \int_0^1 (\frac{p_{j,t}}{p_t})^{-\varepsilon} y_t dj = y_t v_t^p$, where $v_t^p$ captures aggregate price dispersion. With Calvo pricing the dynamics of price dispersion are described by $v_t^p = (1-\theta_p)\Pi^{*-\varepsilon} + \theta_p \Pi_t^{\varepsilon} v_{t-1}^p$. Aggregate final output is then given by:

$$y_t = (1-d(s_t))A_t k_t^{\alpha} h_t^{1-\alpha-\gamma} m_t^{\gamma}/v_t^p. \tag{21}$$

Aggregate household consumption $c_t$ and aggregate labor supply $h_t$ are the weighted averages of consumption and labor by different categories of households and are defined as:

$$c_t \equiv \lambda c_{N,t} + (1-\lambda)c_{R,t}, \tag{22}$$

$$h_t \equiv \lambda h_{N,t} + (1-\lambda)h_{R,t}. \tag{23}$$

Firm profits, transferred to Ricardian households are $F_t = y_t - 1/(1-\alpha-\gamma)w_t h_t$. Finally, the overall resource constraint of the economy reads:

$$y_t = c_t + x_t + g_t + m_t. \tag{24}$$

# 3 Calibration

The model is calibrated to capture some empirically observed moments of the German economy. We specify the parameters of the production sector based on empirical data to match the average ratios of private consumption to GDP and private investment to GDP. Parameters which reflect monetary and fiscal policy are set to match the average inflation rate, the ratio of government consumption to GDP, and the debt to GDP target. Regarding the structural parameters of the model, which capture household preferences and frictions, we largely follow the existing literature on German business cycles. Table 1 summarizes the parameters used in the baseline specification.

The parameters that capture household preferences correspond to the values used by Hristov (2016) and are broadly in line with values used in most studies on the German economy. The subjective discount factor of households, $\beta$, is set to 0.998, the inverse of the intertemporal elasticity of substitution $\rho$ is set to 2 and the inverse of the Frisch elasticity of labor supply $\chi$ is set to 1.5. Following Grabka and Halbmeier (2019), the share of non-Ricardian households $\lambda$ is set to 0.28. Finally, the labor disutility parameters, $\psi_R$ and $\psi_N$, are set as to reach an average working time of $h_t = 0.33$ in the deterministic steady state.

We set the capital share to $\alpha = 0.3$, which corresponds to the average capital share in Germany between 1991–2018 as reported by the Federal Statistical Office (Destatis). Regarding the environmental part of the model, we follow the approach adopted by Fischer and Springborn (2011). They calibrate the production elasticity of polluting intermediate inputs $\gamma$ as to match the average energy expenditure relative to GDP in the United States. We thus set $\gamma = 0.09$, which corresponds to the average total energy supply relative to GDP in Germany for the period from 1990–2020, as reported by the International Energy Agency (IEA). The quarterly depreciation rate of physical capital $\delta$ is set to 0.025. In line with the estimation results of Drygalla et al. (2020) we set the investment adjustment cost parameter $\kappa$ to 3.9. According to the estimation results of Jondeau and Sahuc (2008) for the Germany economy, we set the Calvo parameter to $\theta_p = 0.86$ and the elasticity of substitution between intermediate goods $\varepsilon$ to 6, which corresponds to a markup of 1.2.

For the specification of greenhouse gas dynamics, we follow Golosov et al. (2014) and set $\bar{s}$ to 581 GtC (gigaton of carbon) which corresponds to the pre-industrial concentration of GHG in the atmosphere. Emissions from the rest of the world $\bar{e}^w$ are calibrated as to match a German share of global GHG emissions of 2.5%. The parameter $\delta_s$ is set to 0.0021, implying a half life of atmospheric carbon dioxide of 83 years as suggested by Reilly (1992). The parameter $\eta_s$ in the damage function is set as to reproduce climate damages equal to 0.002438 of GDP in 2020 (see Nordhaus, 2017).

Regarding the choice of the parameters that capture monetary and fiscal policy, we again consider the estimation results of Drygalla et al. (2020). The stance on inflation $\gamma_\Pi$ is set to 1.47 and the degree of interest rate smoothing $\gamma_R$ is set to 0.91. The target rate of inflation is set to 0%. The parameter $\phi_T$ that captures the strength of the reaction of lump-sum transfers to deviations of government debt from target is set to 0.38. The steady state levels of government debt $\bar{b}$ and consumption $\bar{g}$ are set to match a debt-to-GDP ratio of 0.6 and a government consumption to GDP ratio of 0.2. We set $\tau_C = 0.19$ in accordance with the value-added tax rate in Germany and set $\tau_K = 0.26$ to match the overall statutory tax on dividend income as in the legal codes. The tax rate on labor income is set to $\tau_L = 0.2$, which corresponds to the average personal income tax rate in Germany as reported in the OECD tax database.[6] Steady state transfers $\bar{T}$ correspond to the steady state difference between steady state tax income net of government spending and interest rate payments on government debt.

## 4 Climate Policy and Revenue Recycling Schemes

We calibrate the emissions tax rate so as to match the climate goals established by the new German climate law. In June 2021, the German constitutional court has revised the previous legislation, setting more ambitious emissions reduction targets. The country is supposed to reduce its emissions of 65% by 2030 compared to 1990 levels.[7] By looking at emissions data and historical trends, this corresponds to an emissions reduction of 40% compared to 2020 levels.[8] In our analysis we thus take 2020 as starting point and set the emissions tax so as to achieve a 40% reduction in 2030.

To test the double dividend hypothesis, we compare four different schemes. In the first one,

[6] For simplicity, we do not consider variations in value-added tax rates for specific goods. To set the labor tax rate, we compute the average personal income tax rate over the period 2000–2020 for the German mean income excluding social security contributions.

[7] Under the former legislation the emissions reduction target over the same period amounted to 55% relative to 1990. The novel German climate law is summarized here: https://www.bundesregierung.de/breg-de/themen/klimaschutz/climate-change-act-2021-1936846

[8] To compute the targeted emissions reductions, we used the official figures on carbon equivalent emissions from the Umweltbundesamt (UBA).

Table 1: Calibrated Parameters – Baseline Scenario

| Parameter | Value | Description |
|---|---|---|
| Households: | | |
| $\beta$ | 0.998 | Subjective discount factor |
| $\chi$ | 1.5 | Inverse Frisch elasticity |
| $\rho$ | 2 | Inverse elasticity of intertemporal substitution |
| $\psi_R$ | 45 | Labor disutility Ricardian |
| $\psi_N$ | 45 | Labor disutility non-Ricardian |
| $\lambda$ | 0.28 | Share of non-Ricardian households |
| Firms & Environment: | | |
| $\delta$ | 0.025 | Depreciation rate |
| $\gamma$ | 0.09 | Output elasticity polluting goods |
| $\alpha$ | 0.30 | Output elasticity capital |
| $\kappa$ | 3.9 | Investment adjustment costs |
| $\theta_p$ | 0.86 | Price stickiness |
| $\varepsilon$ | 6 | Elasticity of substitution intermediate goods |
| $\bar{s}$ | 581 | Pre-industrial stock of emissions |
| $\eta_s$ | 7.4709e-06 | Scaling parameter climate damages |
| $\delta_s$ | 0.0021 | Decay rate of greenhouse gases |
| Policies: | | |
| $\gamma_\Pi$ | 1.47 | Interest rate rule inflation coefficient |
| $\gamma_R$ | 0.91 | Interest rate rule smoothing coefficient |
| $\bar{\Pi}$ | 1.00 | Target inflation |
| $\phi_T$ | 0.38 | Reaction of transfers |
| $\tau_K$ | 0.26 | Capital income tax rate |
| $\tau_C$ | 0.19 | Value added tax rate |
| $\tau_L$ | 0.2 | Net personal tax rate |
| $\frac{b}{y}$ | 0.6 | Debt-GDP-ratio |
| $\frac{g}{y}$ | 0.2 | Government consumption to GDP ratio |
| Stochastic processes: | | |
| $\rho_a$ | 0.95 | Persistence TFP shock |
| $\rho_g$ | 0.86 | Persistence government spending shock |
| $\sigma_a$ | 0.0049 | S.D. TFP shock |
| $\sigma_R$ | 0.0004 | S.D. Monetary shock |
| $\sigma_g$ | 0.0039 | S.D. Government spending shock |

which we label *Spending*, all revenues from climate policy are channeled into government spending ($\tau_E e_t = \Delta\bar{g}$). Under the second scheme, labeled *Transfer*, all revenues are transferred to both types of households in a lump-sum fashion ($\tau_E e_t = \Delta\bar{T}$). The transfer scheme is one of the most discussed recycling options in the current public debate on climate policy and the baseline standard in the literature on double dividend. We then consider two recycling schemes in which revenues are used to reduce distortionary taxes. In the third scheme, labeled *Capital*, the additional revenues are used to finance a reduction of capital gains taxes ($\tau_E e_t = -\Delta\tau_K(r_{k,t}k_t + F_t)$), while, under the fourth scheme, *Labor*, the revenues are used to finance a reduction of labor income taxes ($\tau_E e_t = -\Delta\tau_L w_t h_t$). To ensure comparability between the different schemes, we model budget-neutral tax reductions and keep transfers, as well as government spending unchanged compared to the no-policy scenario.

In the following we study (i) the short run behavior of the economy under different recycling schemes in response to aggregate shocks; (ii) the steady state macroeconomic and welfare effects of different schemes; (iii) the role of inequality aversion for the welfare evaluation; (iv) the dynamic performance of the schemes along our ten-year mitigation pathway.

## 4.1 Business Cycle and Uncertainty

### 4.1.1 Impulse Response Functions

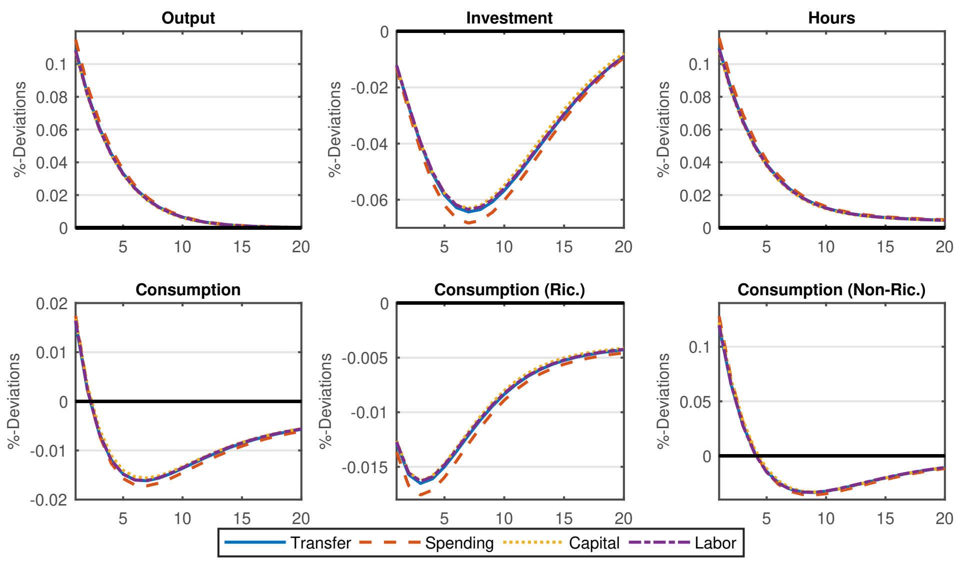
Before jumping to the core of our analysis, we describe here the reaction of the economy to government spending and monetary policy shocks under different recycling schemes. We do not expect large differences in the short-run dynamics of the economy since these schemes mainly affect the steady state of the model. Nevertheless, we think it is useful to show the behavior of the model under two standard shocks analyzed in the business cycle literature. We focus on a government spending shock, since it is strictly connected to the fiscal nature of the analysis conducted in the paper, and on a monetary policy shock, to highlight some of the key transmission mechanisms at place in a New-Keynesian set-up.

Figure 1 displays the response of the main macroeconomic aggregates to a one per cent standard deviation increase in government spending, $g_t$, under different revenue recycling schemes. All results are reported as percentage deviations from the initial steady state over a 20-quarter period. In response to the shock we observe an increase in output and a crowding out effect on investment. Aggregate consumption increases on impact, sustained by the consumption of non-Ricardian households, and then starts decreasing, remaining below the steady state level all along the simulation period. The co-existence of non-Ricardian and Ricardian households and the New Keynesian features of the model explain why the government spending shock succeeds, at least on impact, in stimulating consumption (see e.g. Galí et al., 2007). An increase in government spending lowers the present value of after-tax income, thus generating a negative wealth effect that induces a cut in consumption by Ricardian households. Less resources in the economy are available for private use and households increase their labor supply to offset the negative effects on consumption. The pressure on the labor market slightly raises inflation and this reflects in an increase in the nominal interest rate. Differently from Ricardian households, rule-of-thumb consumers do not smooth their consumption path in the face of fluctuations and do not intertemporally substitute in response to changes in the interest rate.

An increase in government consumption, by fostering an expansion in employment and a consequent rise in the real wage and labor income, increases the consumption of rule-of-thumb households.

We observe very similar responses under the different recycling schemes. The *Spending* scenario, as expected, is the one where the highest contractionary effects on consumption and investment materialize. Using the revenues from climate policy to increase public spending amplifies the transmission of the shock, further reinforcing the crowding out effects on private demand. If the revenues from climate policy are used to reduce taxes on capital, investment and consumption decrease less, even though the differences are negligible.

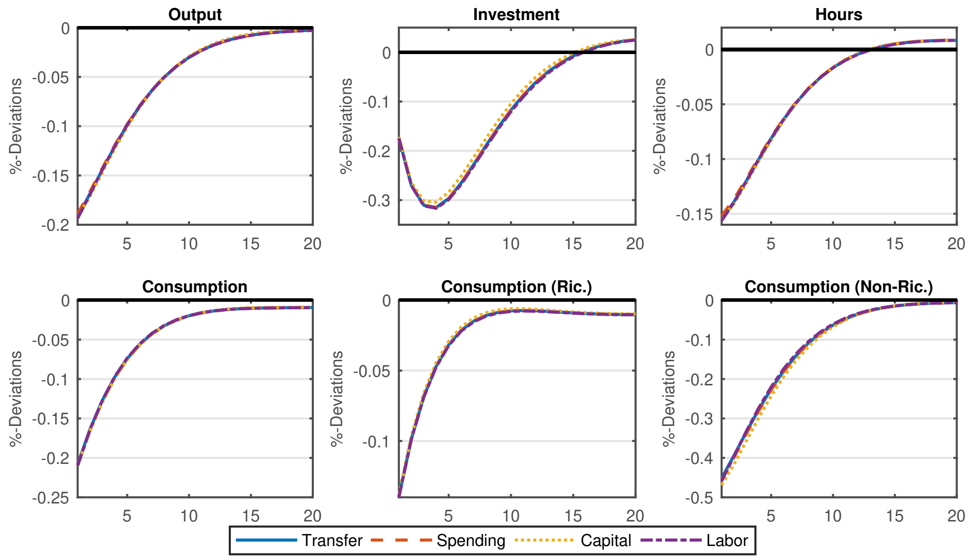
Figure 1: IRFs to a Government Spending Shock




Note: The figure plots the impulse response of the main macroeconomic variables to a positive government spending shock (1%) for different revenue recycling schemes. All variables are expressed as percentage deviations from the steady state. Time is in quarters.

Figure 2 shows the response of the economy to a positive one per cent monetary policy shock. This shock, increasing the real interest rate, depresses aggregate demand and output. Firms reduce the demand for factor inputs. Non-Ricardian households are the one more penalized by the shock, suffering from the shrinkage of their labor income. Also in this case the *Capital* scheme performs slightly better in sustaining investment, but comes with the side effects of further penalizing the consumption of non-Ricardian households and creating higher fiscal imbalances. Redistributing the revenues via the *Labor* scheme, instead, proves to be beneficial for the financially constrained households, easing the contractionary effects on the labor market.

Figure 2: IRFs Monetary Policy Shock




Note: The figure plots the impulse response of the main macroeconomic variables to a negative monetary policy shock (-1%) for different revenue recycling schemes. All variables are expressed as percentage deviations from the steady state. Time is in quarters.

Overall, the IRFs analysis reveals only minor differences between the revenue recycling schemes. Even though revenues from emissions taxes vary in response to business cycle shocks, aggregate dynamics are largely unaffected by the differences across schemes. Given that the choice of the scheme affects the composition of government revenues, but does not affect the fiscal rule, this observation is not too surprising.

#### 4.1.2 Aggregate Effects and Welfare

In this section we provide an overview of the overall economic and welfare costs associated with a 40% emissions reduction and business cycle fluctuations for different recycling schemes. Results are reported in Table 2. As standard in the business cycle literature, welfare is computed from a second order approximation of the theoretical moments of the model (Schmitt-Grohé and Uribe, 2004) and is expressed in consumption equivalent variations relative to the no-policy scenario. To test the double dividend hypothesis, but also to highlight potential trade-offs between efficiency and equity, we report both welfare costs for Ricardian and non-Ricardian households, and aggregate welfare, computed as weighted average of household specific welfare changes.

The results in Table 2 show that, overall, the mitigation plan imposes some costs on the economy.

The distribution of these costs varies across aggregate demand components and household categories, according to the recycling scheme implemented.

We observe the largest output losses under the *Transfer* and *Labor* schemes, mainly driven by a stronger contraction of investments. The *Capital* scheme, vice versa, leads to an increase in investment, which is reflected in a smaller contraction of output. Under the *Spending* scheme we observe a stronger decline of consumption compared to the other schemes. Here, private consumption is crowded out by public expenditures. The reduction of distortionary taxes delivers the same effects on consumption, but a different reaction in investment and labor. Reducing the fiscal pressure on capital pays in terms of investments gains, while reducing taxes on labor income translates into a larger increase in hours worked.

Coming to welfare effects, the *Spending* scheme is the most penalizing, both in terms of aggregate welfare and in terms of welfare of different household types. This result is not surprising: using revenues to increase public consumption is a pure waste from society's viewpoint, due to the unproductive nature of public spending in the model. Under this regime households work more to satisfy the additional demand coming from the public sector and to mitigate the negative effects on consumption. Ricardian households, who smooth consumption over time, are the most penalized by the increase in public spending (see previous section). In comparison, the redistribution via lump-sum transfers alleviates welfare costs, in particular for non-Ricardian households. Looking at the *Capital* and *Labor* schemes, we can confirm the weak version of the double dividend hypothesis: reducing distortionary taxes reduces the overall welfare costs of the mitigation plan. Nevertheless, while aggregate welfare, and the welfare of Ricardian households is always higher under these schemes, for non-Ricardian households the double dividend hypothesis is confirmed only when climate policy revenues are used to reduce taxes on labor. Financially constrained households do not have access to capital markets and are not subject to capital taxation. Hence, these households cannot directly benefit from the *Capital* redistribution scheme.

In light of the debate centering around the study of Lucas (1990), the finding that a reduction of capital income taxes increases macroeconomic efficiency comes as no surprise. Removing the distortion in the process of capital accumulation leads to increases in the stock of capital and an associated stabilization of output. Interestingly, Mankiw (2000) argues that financially constrained households, who do not directly benefit from the capital tax reduction, would still favor this option. Apparently, in the present framework, this is not the case. The explanation for this different result is the relatively smaller share of financially constrained households in the present study. This implies that the capital stock is generally larger, such that the increases in the capital stock, induced by the tax reduction, are smaller. Furthermore, in the present framework firms operate under monopolistic competition and earn profits. This reduces the increase in the real wages associated with the increase of the capital stock. Therefore, financially constrained households benefit more from a labor tax reduction or a lump-sum redistribution.

Quantitatively the differences in the welfare effects between the *Transfer*, the *Capital*, and the *Labor* scheme appear relatively small. To put these numbers into perspective, it is helpful to translate the consumption equivalent variations into monetary units. We compute the average private consumption in Germany between 1991–2018 and compare the results obtained reducing distortionary taxes with the one obtained under the *Transfer* scheme, to account for the size of the weak double dividend in this model. Households save roughly 107 Euros per-capita per year under the *Capital* scheme and roughly 54 Euros under the *Labor* scheme.[9] Hence, compared to a redistribution via transfers, income tax reductions can create relevant efficiency gains.

Table 2: Long run macroeconomic and welfare effects of a 40% emissions reduction

| Scenario | $\Delta y_t$ | $\Delta c_t$ | $\Delta x_t$ | $\Delta h_t$ | $\Delta W_T$ | $\Delta W_R$ | $\Delta W_N$ |
|---|---|---|---|---|---|---|---|
| Spending | -4.6 | -3.8 | -4.6 | 1.2 | -3.6 | -3.7 | -3.5 |
| Transfer | -5.5 | -3.0 | -5.5 | 0.2 | -2.4 | -2.7 | -1.9 |
| Capital | -3.9 | -2.0 | 2.7 | 0.1 | -1.8 | -1.4 | -2.4 |
| Labor | -4.9 | -2.1 | -4.9 | 0.9 | -2.1 | -2.3 | -1.7 |

Note: Changes in macroeconomic aggregates are reported in % changes relative to the no-policy scenario; welfare effects are expressed in terms of consumption equivalent variations relative to the no-policy scenario.

### 4.2 Inequality Aversion and Welfare

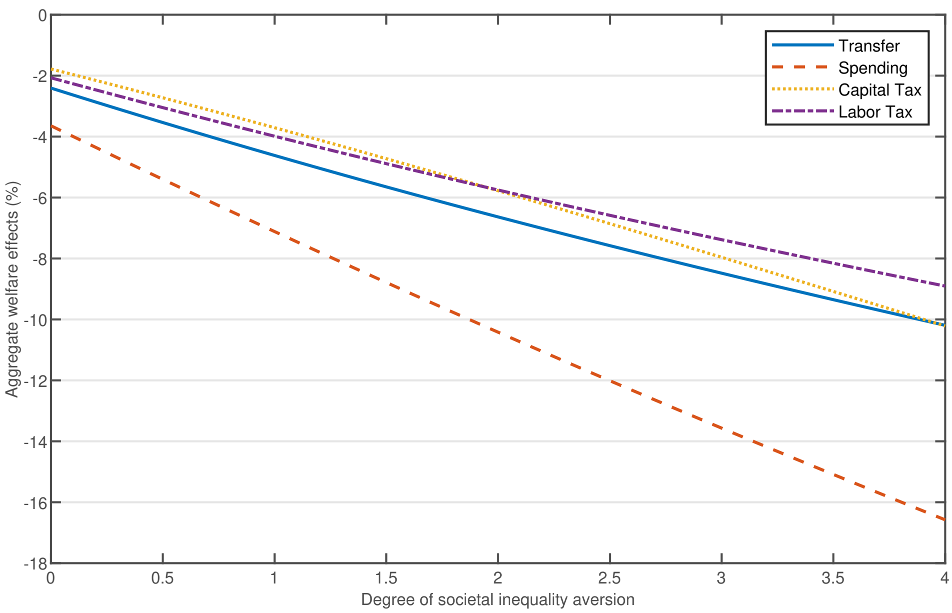
The welfare effects discussed above suggest that the capital gains tax reduction is the superior policy in terms of aggregate welfare. However, we also observe that the welfare effects differ markedly between Ricardian and non-Ricardian households. Clearly, perceptions about fairness and the potentially uneven distribution of the burdens associated with climate policies could undermine the political feasibility of these measures. Whether and how the distribution of the burdens associated with these policies affects the overall perception of these measures is ultimately a normative question. Therefore, as common in the literature on redistribution and social welfare (cf. Le Breton and Weymark, 2011), we examine how varying the degree of inequality aversion affects the assessment of aggregate welfare.

The previously reported welfare results are based on a utilitarian perspective, i.e. we assume that the social welfare function is linear in the individual utility functions. To examine how inequality

[9] These figures are based on average real private consumption in Germany between 1991–2018 (Destatis) and computed for a population of 82 million people (average German population 1991–2020, Destatis) .

aversion affects these results, we relax this assumption and vary the degree of concavity of the social welfare function in the computation of welfare effects. Again, we express welfare in terms of consumption equivalent variations relative to the no-policy scenario. We keep all other parameters unchanged and vary only the aggregate degree of inequality aversion.[10] The results of this exercise are depicted in Figure 3.

Figure 3: Aggregate welfare effects for different degrees of inequality aversion




Note: Aggregate welfare effects relative to the no-policy scenario (% consumption equivalent variations) for different degrees of societal inequality aversion.

Note that welfare costs increase with the degree of inequality aversion under all schemes. This effect is driven by the concavity of the social welfare function and resembles the findings of Hänsel et al. (2021). As can be inferred from the figure, for low degrees of inequality aversion in the range between 0 and 1, the welfare ranking reported above remains unchanged. Starting from a degree of societal inequality aversion around 1.5, we find that aggregate welfare losses are smaller under the *Labor* scheme, compared to the *Capital* scheme. Furthermore, for an inequality aversion of about 4 we also observe smaller aggregate welfare losses under the *Transfer* relative to the *Capital* scheme.

It is not easy to interpret these results, because, while an inequality aversion of 0 corresponds to the Utilitarian perspective, higher values of societal inequality aversion cannot be interpreted in

[10]Details on the computation can be found in the Appendix C.

this way. To put the observed pattern into perspective we can rely on empirical studies that estimate inequality aversion in Germany. As explained by Schwarze and Härpfer (2007) and Bargain et al. (2014), inequality aversion tends to be relatively high in Germany and continental Europe. According to the results of Aristei and Perugini (2016) the parameter of inequality aversion in Germany amounts to roughly 1.4. This value is consistent with the findings of Evans and Sezer (2005) who report inequality aversion parameters in the range between 1.1 and 1.7 for Germany. Overall, these estimates are also consistent with the findings reported by Atkinson et al. (2009) and the meta-analysis of Del Campo et al. (2021) covering a broad range of countries. Thus, taking normative considerations into account and relying on these studies reveals that the differences in aggregate welfare between the *Labor* scheme and the *Capital* scheme vanish. In the upper range of the parameter distribution, the *Labor* scheme is preferable from an aggregate perspective.

### 4.3 Transitional Dynamics

After analyzing the performance of different recycling schemes in response to business cycle shocks and the aggregate effects of a 40% emission reductions in the presence of business cycle uncertainty, we now focus on transitional dynamics over the period 2020–2030. As explained, this time window is consistent with the emissions reduction targets set by the German government. We abstract here from other sources of uncertainty and focus exclusively on the effects of the environmental regulation. We conduct a perfect-foresight experiment, in which the carbon tax and the corresponding revenue recycling schemes are introduced at the beginning of 2020. In accordance with the yearly emissions reduction goals stated in the German climate law, carbon tax increases gradually over the period until the 2030 target is reached.

Figure 4 shows the transition dynamics of our economy. Following the introduction of the tax we observe a drop in output, consumption, and labor, independently of the redistribution scheme in place. The increase in the emissions tax rate raises the user costs of polluting intermediate goods, leading firms to adjust all the factor inputs. When the policy shock hits the economy, part of the firms cannot adjust goods prices and thus react by reducing production. The inability to fully adjust prices also explains the observed kinks at the beginning of the transition process.[11] The demand for labor declines, bringing down marginal costs and inflation and putting downward pressure on wages, that decrease substantially in the first quarter and remain persistently below the steady state along all the mitigation period. The drop in the real interest rate in the first period prevents a consequent drop of investments, at least on impact. Nevertheless, the behavior of investment during the transition differs

[11] For comparison, Appendix D shows the transitional dynamics and the corresponding welfare effects under fully flexible prices. As can be inferred, in absence of price rigidities, transitional dynamics are smoothed and the welfare costs of climate policy are reduced. However, the relative performance of different recycling schemes does not change.

considerably conditional on the redistribution scheme implemented. If the revenues from climate policy are used to reduce the capital tax, we observe an expansion of investment and an increase in the demand for capital. The increase in investment under the *Capital* scheme explains the lower decline in output compared to the other schemes. Furthermore, the increase in investment translates in higher capital stock. This allows us to expand production and firms increase their labor demand, which explains the higher wages under the *Capital* scheme.

The *Labor* scheme, favoring both types of households, helps in sustaining consumption over the entire transition period. However, we observe a relatively stronger decline in output compared to the *Capital* scheme, which results from the decrease in investment. In accordance with theory, we find that after an initial drop, labor hours steadily increase in response to the reduction in labor income taxes. After around half of the transition period, hours worked have recovered from the initial decline and subsequently increase further until they reach a roughly 0.8% higher level in 2030. The *Transfer* scheme is the one performing worst in terms of output, labor, and investment. However, the increase in transfers limits the initial drop in consumption and allows for higher consumption over the entire period compared to the *Spending* scheme. Under the *Spending* scenario we observe the usual strong crowding out effects of increases in government spending on private consumption. To meet the higher aggregate demand, coming from the public sector, firms employ relatively more capital and labor. This mitigates the decline in output under the *Spending* scheme.

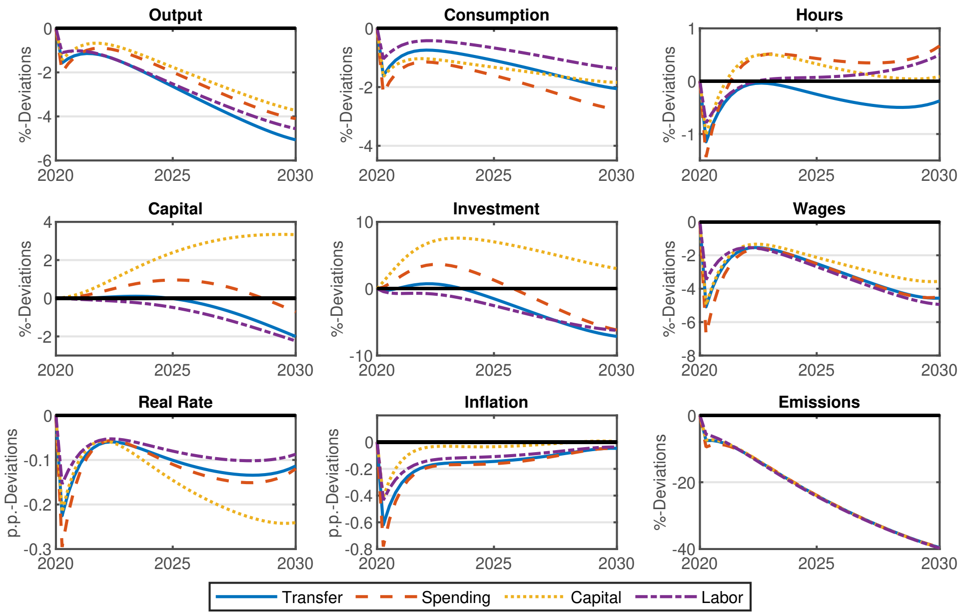
Table 3 shows the welfare costs of the transition at different time horizons.[12] The first thing to notice is that, while the total welfare costs and the welfare costs of Ricardian households tend to increase along the transition, regardless of the redistribution scheme, for non-Ricardian households the results point in the opposite direction and are less clear cut. The finding that the initial welfare costs of the transition are relatively large for non-Ricardian households and comparably small for Ricardian households vividly reflects the effects of consumption smoothing.[13] In response to the decline of income at the onset of the transition Ricardian households smooth consumption and limit the initial welfare losses. In contrast, due to the inability of non-Ricardian households to smooth consumption, they are fully exposed to the adverse income effects. Subsequently, the recovery of labor markets mitigates the welfare losses of non-Ricardian households.

In terms of the welfare effects at the different time-horizons, the *Labor* scheme is clearly the most efficient option. The level of aggregate consumption is higher under this scheme. Moreover, after an initial drop, wages raise again, sustaining labor income and consumption of non-Ricardian households, who do not suffer directly from contemporaneous reductions in investment. Thus,

[12]Details on welfare computation are provided in Appendix C.

[13]In Appendix D we show that in the absence of price rigidities, most of the welfare costs are, instead, borne by Ricardian households.

Figure 4: Transition dynamics of the main variables between 2020–2030




Note: The figure plots the simulated time path of the main macroeconomic variables for a carbon tax achieving a 40% emissions reduction in ten years, under different revenues recycling schemes. All variables are expressed as percentage deviations from the steady state with the exception of the real rate and the inflation rate, reported in percentage point deviations from the steady state. Time is in quarters.

regardless of the horizon, non-Ricardian households prefer the *Labor* scheme. Since the effects of the labor tax reduction manifest directly, the same holds for Ricardian households.

Redistribution via lump-sum transfers seems to alleviate the welfare costs at the medium stage of the transition. As can be inferred Ricardian households tend to prefer this option over the capital tax reduction in the short- and medium-run. However, over the full transition period their welfare losses under the *Capital* scheme are slightly smaller. The reason behind this observation is the nature of the capital tax reduction. Compared to the *Transfer* scheme or the *Labor* scheme, the effects of the capital tax reduction require longer time to materialize.

Finally, in line with the transition dynamics described above, the *Spending* scheme is the most costly in terms of welfare, due to its detrimental effects on consumption.

Table 3: Welfare effects over the transition period

| | 2 Years | | | 5 Years | | | 10 Years | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | $\Delta W_T$ | $\Delta W_R$ | $\Delta W_N$ | $\Delta W_T$ | $\Delta W_R$ | $\Delta W_N$ | $\Delta W_T$ | $\Delta W_R$ | $W_N$ |
| Spending | -1.27 | -0.66 | -2.85 | -1.48 | -1.38 | -1.72 | -2.00 | -1.99 | -2.01 |
| Transfer | -0.75 | -0.25 | -2.05 | -0.77 | -0.68 | -1.00 | -1.04 | -1.08 | -0.91 |
| Capital | -1.08 | -0.70 | -2.05 | -1.28 | -1.27 | -1.32 | -1.51 | -1.46 | -1.65 |
| Labor | -0.44 | -0.06 | -1.43 | -0.49 | -0.39 | -0.75 | -0.82 | -0.84 | -0.79 |

Note: Welfare effects are expressed in terms of consumption equivalent variations relative to the no-policy scenario at different time horizons ($t = 8, 20, 40$).

# 5 Conclusion

Reducing greenhouse gas emissions is unavoidable if we want to keep global warming well below 2°C . Market-based climate policy instruments, such as emissions taxes and permit trading systems, are key tools to achieve this. Attaching a price to emissions creates incentives for economic actors to engage in abatement activities and mitigation efforts. In addition, the revenues generated in this way can be used to shape the transition process politically.

The present paper examines the performance of different revenue recycling schemes from a macroeconomic perspective. Our analysis is based on a New-Keynesian DSGE model which incorporates several economic imperfections and allows us to distinguish between financially constrained and unconstrained households. The comparison of alternative uses of climate policy revenues within this framework relates to the debate about distributional effects of climate policies and adds to the literature on the double dividend hypothesis. Furthermore, the analysis complements the growing E-DSGE literature by providing a detailed assessment of the dynamic implications of revenue recycling schemes.

With respect to short-run dynamics we find that different recycling schemes exert only minor effects on the response of the economy to standard business cycle shocks. In the long run, when accounting for the aggregate effects of uncertainty and mitigation costs, a weak double dividend can be confirmed: reducing distortionary taxes reduces aggregate welfare costs more than a redistribution via lump-sum transfers. Nevertheless there are non trivial distributional effects related to the choice of specific recycling schemes. In particular Ricardian and non-Ricardian households favor reductions in labor income taxes over lump-sum transfers, but reductions in capital income taxes are only favorable for Ricardian households. Thus, even though capital gains tax reductions are found to be the preferable option to reduce welfare costs from an aggregate perspective, the larger relative costs are borne by financially constrained households. Even if labor tax reductions yield a relatively smaller welfare advantage compared to capital taxes reductions, this option allows to take equity aspects into account: both types of households are better off compared to redistribution via lump-sum transfers. Nevertheless, it is important to emphasize that in the model all households earn labor income and thus directly benefit from labor tax reductions. We abstract from unemployment and do not consider households that solely depend on transfer income. These categories of households would not benefit from tax reductions and would likely favor a redistribution via lump-sum transfers. Furthermore, from a feasibility perspective, it is important to consider that a redistribution via transfers is potentially more transparent than a redistribution via tax reductions. Households can easily recognize a transfer as a direct compensation related to climate policy, which can be important to ensure a broad support for such measures from a behavioral perspective.

To shed more light on the aggregate effects and the distributional implications of different recycling options, we examine how inequality aversion can shape welfare results. Specifically, we assume a concave social welfare function and vary the degree of inequality aversion. Compared to the welfare results obtained under the baseline specification from an Utilitarian perspective, higher inequality aversion tilts the aggregate welfare effects towards the labor tax reduction. In the empirically relevant parameter range for Germany, welfare effects from reducing labor income or capital gains taxes are comparable.

Finally, when we abstract from uncertainty and take transitional dynamics into account, our analysis reveals that a weak double dividend materializes only when revenues from climate policy are used to reduce taxes on labor. Our transition experiment shows that capital gains tax reductions are kind of front loading the burden (generating higher initial consumption losses), while labor tax reductions require lower initial consumption reductions. The benefits from reducing capital taxation manifest at later stages of the mitigation period and only for richer households. This result suggests that, along the transition, using climate policy revenues to reduce distortionary taxes on labor income decreases the welfare costs of climate actions, overall and for different categories of households, so addressing concerns regarding the regressive effects of climate policy. From a policy perspective this finding is particularly relevant if we consider that ambitious climate policies should be implemented in the short and medium run and most of the revenues collected through carbon taxes are going to be distributed mostly during the first mitigation window. The decarbonization of the economies should progressively reduce the tax base for this type of revenues, making a redistribution scheme whose positive effects materialize in the long run less appealing to manage the costs of the transition and its social acceptability.

To sum up, we find that the distributional effects of emissions taxation are crucially determined by the choice of the redistribution scheme. While a weak double dividend for all households can be achieved via a labor tax reduction, a capital tax reduction exerts regressive effects and benefits mostly wealthy households. Furthermore, we show that the efficiency gains from a capital gains tax reduction materialize only over a longer horizon. Finally, it is important to emphasize that our analysis focuses on standard redistribution policies and excludes other options such as direct investment subsidies for green technologies or research funding. Moreover, the present framework takes a cost-efficiency perspective and abstracts from potential damages associated with climate change. Extending this framework to incorporate climate impacts and green supply-side measures are promising avenues for future research.

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# A Full Model

To solve the model we rewrite (17) in terms of $g_{1,t}$ and $g_{2,t}$ recursively. The full set of equilibrium conditions of the model is summarized below:

$$\lambda_{R,t} = c_{R,t}^{-\rho}(1+\tau_c)^{-1}, \tag{A-1}$$

$$\psi_R h_{R,t}^{\chi} = \frac{(1-\tau_L)}{(1+\tau_c)} c_{R,t}^{-\rho} w_t, \tag{A-2}$$

$$\lambda_{R,t} = \beta R_t E_t \lambda_{R,t+1} \Pi_{t+1}^{-1}, \tag{A-3}$$

$$1 = q_t \left[1 - \frac{\kappa}{2}\left(\frac{x_t}{x_{t+1}} - 1\right)^2 - \kappa\left(\frac{x_t}{x_{t-1}} - 1\right)\frac{x_t}{x_{t-1}}\right] + \beta E_t \frac{\lambda_{R,t+1}}{\lambda_{R,t}} q_{t+1} \kappa \left(\frac{x_{t+1}}{x_t} - 1\right)\left(\frac{x_{t+1}}{x_t}\right)^2, \tag{A-4}$$

$$q_t = \beta E_t \frac{\lambda_{R,t+1}}{\lambda_{R,t}} \left[(1-\delta)q_{t+1} + (1-\tau_k)R_{K,t+1}\right], \tag{A-5}$$

$$(1+\tau_c)c_{N,t} = (1-\tau_L)w_t h_{N,t} + T_t, \tag{A-6}$$

$$h_{N,t}^{\chi} = \frac{(1-\tau_L)}{\psi_N(1+\tau_c)} c_{N,t}^{-\rho} w_t, \tag{A-7}$$

$$c_t = \lambda c_{N,t} + (1-\lambda)c_{R,t}, \tag{A-8}$$

$$h_t = \lambda h_{N,t} + (1-\lambda)h_{R,t}, \tag{A-9}$$

$$k_{t+1} = \left[1 - \frac{\kappa}{2}\left(\frac{x_t}{x_{t-1}} - 1\right)^2\right] x_t + (1-\delta)k_t, \tag{A-10}$$

$$y_t = (1-d(s_t))A_t k_t^{\alpha} h_t^{1-\alpha-\gamma} m_t^{\gamma} / v_t^p, \tag{A-11}$$

$$\left(\frac{k_t}{h_t}\right) = \frac{\alpha}{(1-\alpha-\gamma)} \frac{w_t}{r_{k,t}}, \tag{A-12}$$

$$\left(\frac{m_t}{h_t}\right) = \frac{\gamma}{(1-\alpha-\gamma)} \frac{w_t}{(1+\tau_E)}, \tag{A-13}$$

$$mc_t = \left[\frac{1}{(1-\alpha-\gamma)}\right]^{1-\alpha-\gamma} \left(\frac{1}{\alpha}\right)^{\alpha} \left(\frac{1}{\gamma}\right)^{\gamma} \frac{w_t^{1-\alpha-\gamma} r_{k,t}^{\alpha} (1+\tau_E)^{\gamma}}{((1-d(s_t))A_t)}, \tag{A-14}$$

$$1 = (1-\theta_p)\Pi_t^{*1-\varepsilon} + \theta_p \Pi_t^{\varepsilon-1}, \tag{A-15}$$

$$v_t^p = (1-\theta_p)\Pi^{*-\varepsilon} + \theta_p \Pi_t^{\varepsilon} v_{t-1}^p, \tag{A-16}$$

$$g_{1,t} = mc_t y_t + \theta_p \beta \frac{\lambda_{R,t+1}}{\lambda_{R,t}} \Pi_{t+1}^{\varepsilon} g_{1,t+1}, \tag{A-17}$$

$$g_{2,t} = y_t + \theta_p \beta \frac{\lambda_{R,t+1}}{\lambda_{R,t}} \Pi_{t+1}^{\varepsilon-1} g_{2,t+1}, \tag{A-18}$$

$$\Pi^* = \frac{\varepsilon}{(\varepsilon-1)} \frac{g_{1,t}}{g_{2,t}}, \tag{A-19}$$

$$F_t = y_t - \frac{1}{(1-\alpha-\gamma} w_t h_t, \tag{A-20}$$

$$\frac{R_t}{\bar{R}} = \left(\frac{R_{t-1}}{\bar{R}}\right)^{\gamma_R} \left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\gamma_\Pi(1-\gamma_R)} exp(\varepsilon_{R,t}), \tag{A-21}$$

$$g_t + R_{t-1}b_{t-1}/\Pi_t = b_t - T_t + \tau_L w_t h_t + \tau_k(r_{k,t}k_t + F_t) + \tau_c c_t + \tau_E m_t, \tag{A-22}$$

$$T_t = \bar{T} - \phi_T(b_t - \bar{b}), \tag{A-23}$$

$$y_t = c_t + x_t + g_t + m_t, \tag{A-24}$$

$$s_t - \bar{s} = (1-\delta_s)(s_{t-1} - \bar{s}) + m_t + m_t^w \tag{A-25}$$

$$1 - d(s_t) = exp(-\eta_s(s_t - \bar{s})) \tag{A-26}$$

$$g_t = (1-\rho_g)\bar{g} + \rho_g g_{t-1} + \varepsilon_{g,t}, \tag{A-27}$$

$$A_t = \rho_a A_{t-1} + \varepsilon_{a,t}. \tag{A-28}$$

# B Data and Sources

The model is calibrated to match long run averages of specific macroeconomic characteristics of the German economy. To this end, we use data from various sources. To ensure consistency, all computations are based on price and seasonally adjusted data. Table B.1 summarizes the used data and sources.

Table B.1: Description of data and data sources

| Variable | Description | Source |
|---|---|---|
| Capital share | Average share of national income going to capital (1991–2018) | Destatis |
| GDP | Gross Domestic Product (1991–2018) | Destatis |
| Private consumption | Private consumption (1991–2018) | Destatis |
| Government consumption | Government consumption (1991–2018) | Destatis |
| Energy expenditures | Total energy supply by GDP (1990–2020) | IEA |
| Labor tax rate | Average personal income tax rate (2000–2020) | OECD |
| Non-Ricardian share | Share of households with zero (or negative) net worth (2017) | DIW (SOEP) |
| Emissions | Greenhouse gas emissions (1990–2020) | UBA |

# C Welfare Measures

We express the household specific welfare effects in terms of consumption equivalent variations relative to the no-policy scenario. We compute the necessary percentage reduction in discounted household consumption, $\Delta$, under the no-policy scenario, which makes households indifferent between different recycling policy scenarios and the no-policy. Given additive-separable preferences, we solve for $\Delta$ the following identity:

$$E_t\left[\sum_{t=0}^{\infty}\beta^t u^{\text{np}}((1-\Delta)c_{i,t},h_{i,t})\right] = E_t\left[\sum_{t=0}^{\infty}\beta^t u^p(c_{i,t},h_{i,t})\right],$$

where the subscript $i$ denotes the household type and and the superscripts np and p indicate the no-policy and policy regime respectively.

To measure aggregate welfare effects, we employ a social welfare function. Since we assume that all households have identical iso-elastic preferences, we adopt a social welfare function with similar properties, i.e. a constant degree of societal inequality aversion $\eta$. Specifically, we assume a social welfare function of the form:

$$u_T = \lambda(1-\rho)^{-\eta}\frac{u_N^{1-\eta}}{1-\eta} + (1-\lambda)(1-\rho)^{-\eta}\frac{u_R^{1-\eta}}{1-\eta},$$

where $u_i$ denotes utilities. As explained in Kaplow (2010), this modification of the social welfare function takes the relationship between the curvature of household specific utility and societal inequality aversion into account. Note that in the case of $\rho = 1$ the underlying utility function will be logarithmic, such that $u_T$ will be well defined. If not indicated differently, we assume $\eta = 0$ which corresponds to a Utilitarian type of social welfare function.

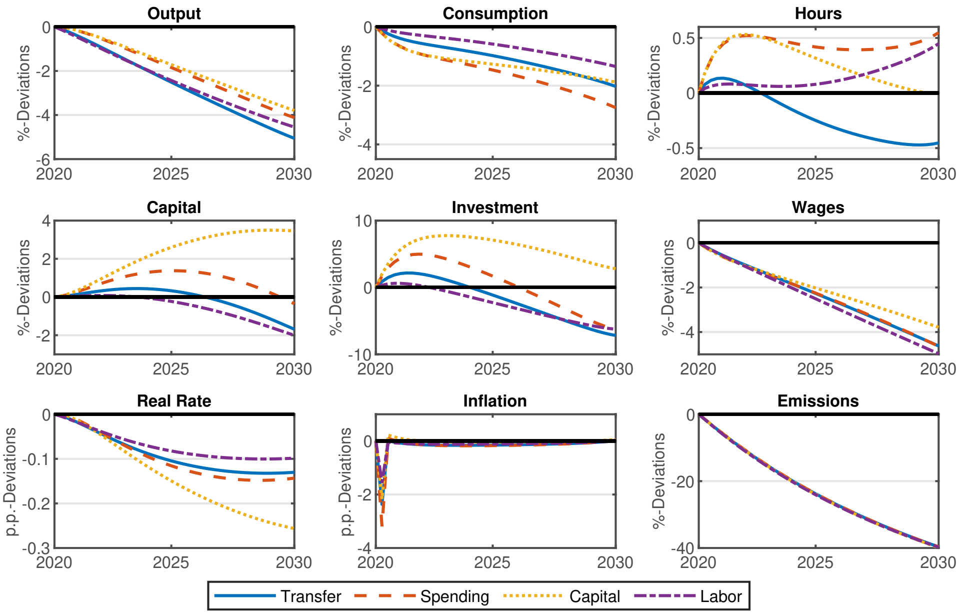
Lastly, to compute the welfare effects of climate policies over the transition period at different time horizons, we solve for $\Delta$ the following identity::

$$\sum_{t=0}^{T}\beta^t u^{\text{np}}((1-\Delta)c_{i,ss},h_{i,ss}) = \sum_{t=0}^{T}\beta^t u^p(c_{i,t},h_{i,t}).$$

Hence, for every $t$, we obtain the required consumption equivalent variations that make households indifferent between the policy regime and the no-policy scenario.

# D The Role of Price Rigidities

Figure D.1: Transition dynamics of the main variables between 2020–2030 (no price rigidities)




Note: The figure plots the simulated time path of the main macroeconomic variables for a carbon tax achieving a 40% emissions reduction in ten years, under different revenues recycling schemes and in the absence of price rigidities. All variables are expressed as percentage deviations from the steady state with the exception of the real rate and the inflation rate, reported in percentage point deviations from the steady state. Time is in quarters.

Table D.2: Welfare effects over the transition period (no price rigidities)

| | 2 Years | | | 5 Years | | | 10 Years | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | $\Delta W_T$ | $\Delta W_R$ | $\Delta W_N$ | $\Delta W_T$ | $\Delta W_R$ | $\Delta W_N$ | $\Delta W_T$ | $\Delta W_R$ | $W_N$ |
| Spending | -0.75 | -0.87 | -0.45 | -1.18 | -1.43 | -0.54 | -1.76 | -1.97 | -1.23 |
| Transfer | -0.37 | -0.44 | -0.22 | -0.55 | -0.73 | -0.08 | -0.86 | -1.08 | -0.29 |
| Capital | -0.76 | -0.91 | -0.39 | -1.12 | -1.34 | -0.57 | -1.40 | -1.47 | -1.20 |
| Labor | -0.20 | -0.21 | -0.16 | -0.35 | -0.45 | -0.10 | -0.70 | -0.84 | -0.34 |

Note: Welfare effects are expressed in terms of consumption equivalent variations relative to the no-policy scenario at different time horizons ($t = 8, 20, 40$), in the absence of price rigidities.