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THIRD-BEST CARBON TAXATION:

Trading off emission cuts, equity, and efficiency*

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Abstract

We analyse carbon taxes, lump-sum climate dividends, and changes to the level and progressivity of the income tax system that optimally trade off carbon emissions, equity, and efficient raising of public revenue while preserving budgetary neutrality and not using individualized lump-sum transfers. Such "third-best" policies include a carbon tax that exceeds the Pigouvian level and recycling of all carbon tax revenue via climate dividends for high (and our preferred) degrees of inequality aversion, even if this implies higher income taxes to meet existing revenue requirements. The carbon tax, climate dividends, and the progressivity of the income tax rise with the degree of inequality aversion. Our results are derived from a micro simulation model estimated from German data, which includes heterogenous households, an Exact Affine Stone Index demand system, and endogenous labour supply. We decompose the welfare effects of policy into emissions, equity, and efficiency components for different degrees of inequality aversion and climate damages.

Keywords: EASI demand system, recycling carbon tax revenue, inequality aversion, efficiency, equity, third-best carbon tax

JEL codes: D12, D31, D62, D63, H23, J22, Q5

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1. Introduction

Pricing carbon is an effective policy to cut greenhouse gas emissions. However, apart from some countries taxing carbon (e.g. Sweden, Switzerland, Finland, Norway, and France) and others with carbon permit schemes (e.g. the European Union and China), policy initiatives have been unambitious and piecemeal. In 2023 24.6 % of global emissions are priced on average at \$22.3/tCO_2e, which implies an average global carbon price of only \$5.5/tCO_2e (IMF, 2023). This is a fraction of the carbon price needed to keep global mean temperature below the target of 2 or 1.5 degrees Celsius above preindustrial levels as agreed upon in the Paris Climate Agreement or below the social cost of carbon (e.g., Rennert et al., 2022).

Carbon pricing's regressive nature is one of the reasons why politicians' appetites remain weak.[1] Price increases on fossil inputs raise living costs for lower income earners more than those earning at the middle and the top, with many already suffering from energy poverty.[2] Hence, many governments have combined carbon pricing with uniform non-individualised transfers, referred to as *climate dividends* (Keohane, 2009).[3] Other uses of carbon tax revenue are earmarking for green investments or lowering income taxes.[4]

We ask if such green tax reforms make economic sense. First, we build a simulation model with heterogenous households, an income tax function that captures a detailed income tax system, multiple consumer goods with different carbon intensities, and an estimated demand system flexible enough to allow for nonlinear Engel curves and an estimated labour supply schedule. Second, we analyse tax reforms that do not try to reform an

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[1] Other reasons include the lobbying influence of incumbent industries, short political horizons, the lack of international coordination, political polarisation, and poor understanding of the effects of carbon pricing. Douenne and Fabre (2022) find that after the Yellow Vests movement, French people would largely reject a carbon tax whose revenues are redistributed uniformly to each adult. But they argue that changing people's beliefs can substantially increase support.

[2] Indexation of government transfers to inflation can protect lower income earners and blunt the regressivity of carbon pricing (Fullerton et al., 2012). In Germany social transfers and wages of low-income workers are at least implicitly indexed. Appendix D considers this case.

[3] Canada (four provinces and two territories) and Switzerland have adopted a market-based system of *carbon fees and dividends*. Such systems have gained interest globally as an equitable way of cutting emissions. The idea is to have no exemptions, apply it to all economic sectors, and for it to be budgetary neutral. Switzerland rebates two thirds of carbon tax revenues; the rest is spent on building energy efficiency and clean energy; transportation is excluded. Austria's carbon tax of €45/tCO2 is rebated as a region-specific dividend of €110-€220 per adult and year. Such policies are also advocated by the Citizens' Climate Lobby and the Climate Leadership Council in the US, where 70% of households are better off under a carbon tax of US\$49/tCO2e when combined with a climate dividend of US\$583 per person (Cronin et al., 2019).

[4] Woerner et al. (2023) provide incentivised experiments for Germany that indicate that a climate dividend receives more support when carbon tax revenue is used to fund tax and dividend schemes, the general budget, or earmarked revenues for green projects.

existing non-optimal income tax but use carbon tax revenue to undertake three different recycling scenarios. Third, we derive and quantify optimal trade-offs between emissions cuts, equity, and efficiency for these three scenarios. Policymakers maximise social welfare and choose income taxes, carbon taxes, and climate dividends on the macroeconomic level, taking full account of the effects at the microeconomic level. Fourth, we impose the constraint that the cost of climate dividends and adjusting the income tax system cannot exceed carbon tax revenue, and thus study optimal green tax reform and refer to our analysis as *third-best optimal carbon taxation*. This distinguishes our analysis from first-best optimal policies where it is assumed that policy makers have full access to individualised lump-sum transfers/finance and from second-best optimal policies where policy makers only have access to uniform lump-sum transfers/finance. Hence, the difference between third-best and second-best optimal policies is that there is the additional constraint of carbon-revenue neutral tax reform.[5]

We permit the government to hand back carbon tax proceeds through climate dividends, which improve equity as tax-paying low-income households benefit proportionally more from this and other low-income households do not pay income taxes. We also allow the government to adjust the income tax system and improve efficiency or equity by changing the level and progressivity of the income tax. We distinguish three scenarios for recycling carbon tax revenue where the net carbon tax revenue is optimally used to fund (i) a lump-sum climate dividend for all households, (ii) a climate dividend and adjusting the level and progressivity of the income tax, and (iii) adjusting the income tax. We show how third-best carbon tax reform in each of the three recycling scenarios depends on the social welfare weights assigned across the income distribution.

We find that the use of climate dividends is generally supported by our simulation results. In all scenarios, the carbon tax is below the social marginal damage of emissions except if inequality aversion is high or damages are low enough. For scenario (i), we find that the policy of pricing carbon and rebating the revenue as climate dividends curbs emissions and offsets some of the adverse effects on the equity of regressive carbon taxes. It also curbs economic activity and requires some of the revenue to be used to make up for the shortfall in income taxes. In scenario (ii), where income taxes can be adjusted to cover the shortfall from carbon taxation, the carbon tax increases and all of its revenue is used for

[5] Some would argue that our third-best policies are just second-best policies with two constraints, but we prefer to use third-best policies to highlight the additional constraint of carbon-neutral tax reform.

climate dividend payments. Scenario (iii), which relies on lowering income taxes when raising carbon taxes, has higher welfare than scenario (i) if inequality aversion is low and vice versa. Our modelling results support policies that prioritise recycling carbon tax revenue fully via climate dividends, even if this implies higher income taxes to meet existing revenue requirements. We show that the carbon tax and climate dividend generally increase with inequality aversion but that carbon taxes are flat when their revenue must be spent on lowering income taxation. We decompose the welfare implications of our three policy scenarios into efficiency, equity, and green components for different degrees of inequality aversion and climate damages to clearly indicate the trade-offs faced by policymakers.

As in van der Ploeg et al. (2022), we use the German consumption expenditure survey (EVS) to estimate empirically an Exact Affine Stone Index (EASI) disaggregated consumer demand system (Lewbel and Pendakur, 2009) for key carbon-intensive consumption categories (e.g. electricity, heating, transport) and some other consumption goods categories. We also estimate a labour supply function, which changes with the after-tax consumption wage and the disutility of labour on household utility. Furthermore, we use German carbon footprint data to match the carbon content of consumption bundles and to estimate the effect of carbon taxation on consumer prices and household expenditure. Unlike van der Ploeg et al. (2022), who focus on the recycling options of a fixed carbon tax and their distributional implications, we extend the model to study third-best optimal policy scenarios. Further improvements in our earlier study are the consideration of supply-side effects of carbon pricing and a better income tax schedule, both of which greatly influence the equilibrium level of the carbon tax, and the consideration of public aversion to income inequality using distributional weights.

Relation to literature Microeconomic simulations of carbon tax incidence typically take policy choices as given when evaluating their distributional effects and are usually not based on well-defined disaggregated demand systems; e.g. the effects of an exogenous policy change are simulated and the necessary rebalancing of expenditure to respect budget constraints (of households and the government) in the face of policy-induced price changes is ignored (e.g. Cornin et al., 2019; Feindt et al., 2021). In contrast, macroeconomic simulations often assume a single representative household when studying the trade-offs of an optimal carbon tax (e.g. Barrage, 2019). Our study is situated between these approaches. We assume, on the microeconomic level, that households' expenditure respects the laws of a disaggregated consumer demand system, labour supply is endogenous, existing income tax policy is accounted for, emissions depend on disaggregated consumption, and that the supply side abates emissions as carbon taxes increase.

Our results contribute to the literature on optimal taxation of an environmental externality in the presence of other distortions (i.e. the "double dividend" literature) and the distributional incidence of environmental taxes. Our distinguishing features from contributions on the latter (e.g. Poterba, 1991; Metcalf, 1999; West and Williams, 2004; Bento et al., 2009; Grainger and Kolstad, 2010; Rausch et al. 2011; Fullerton et al., 2012; Fluess and Thomas, 2015; Williams et al., 2015; Rausch and Schwarz, 2016; Cronin et al., 2019; Pizer and Sexton, 2019; Berry, 2019; Winter et al., 2019; Feindt et al., 2021) are that we have endogenous disaggregated commodity demand and labour supply responses when studying the effects of a carbon tax, climate dividends, and income tax reform. A limitation of our analysis, however, is that we are unable to take a lifetime income perspective, nor do we distinguish different forms of factor income and government transfers. The former makes a carbon tax less regressive (e.g. Hassett et al., 2009) or progressive (Andersson and Atkinson, 2019). The latter are important, since, in general equilibrium, a carbon tax is less regressive if it reduces the ratio of the rental rate to the wage rate (e.g. Rausch et al., 2011; Goulder et al. 2019), and if the government indexes welfare programs that are a higher share of lower-income household incomes to price inflation following a carbon tax (Fullerton et al., 2012). While data limitations prohibit us from considering these aspects in detail, robustness checks in Appendix D show that these are likely to have small effects on our results.[6]

The literature on the "double dividend" shows that using the revenue of a higher pollution tax to cut the labour income tax rate reduces emissions but boosts unemployment, unless the burden of taxation can be shifted to inactive households or fixed factors of production; or if the pre-existing pollution tax is too low and the labour income tax too high (e.g. Bovenberg and de Mooij, 1994; Bovenberg and van der Ploeg, 1994, 1998ab; Goulder, 1995; Bovenberg, 1999). We similarly consider optimal pollution taxes in the presence of other distortions, but we focus on policy reform and permit heterogeneous households rather than a representative agent setup to analyse the emissions-efficiency-equity trade-

[6] Labrousse and Perdereau (2023) suggest that carbon taxes are regressive for households but progressive for firms. They also argue that geography may be important for equity when rebating carbon tax revenue.

off. While we do not allow for a fully optimal nonlinear income tax (Mirrlees, 1971), we optimise the parameters of a specific income tax schedule (Benabou, 2002; Heathcote et al., 2014) and the carbon tax. Our model is closely related to that studied by Cremer et al. (2003), who find that the optimal carbon tax is much below the Pigouvian level when carbon tax revenues are returned by lowering existing taxes (while keeping relative tax shares across household types constant). Our results echo this finding and show that including lump-sum climate dividends increases the carbon tax.

Section 2 sets up our model for analysing third-best carbon taxation and shows how revenue can be recycled via a climate dividend or by lowering the income tax burden when starting with pre-existing taxes. Section 3 presents the estimates of an EASI disaggregated consumer demand system, labour supply, the calibration of the income tax schedule, and the emissions intensities of commodities. Section 4 discusses the third-best optimal carbon tax policies for three different recycling scenarios. Section 5 discusses how the different policy scenarios affect social and private welfare. Section 6 discusses the robustness of our results to factor price changes and the indexation of social welfare payments to price inflation in response to climate policy. Section 7 concludes and suggests areas for further research.

2. A micro-based model of third-best carbon taxation

We specify a model of disaggregated consumer demand, labour supply, income taxation, and emissions for a large group of households, building on the model put forward by van der Ploeg et al. (2022). The supply of products to consumers is infinitely elastic and producer prices are constant. Emission intensities of individual products are endogenous and decrease with the carbon tax. Demand for individual products follows from an EASI disaggregated consumer demand system (Lewbel and Pendakur, 2009). Labour supply depends on the real after-tax consumption wage. Income taxation follows from the reduced-form function for disposable income put forward by Benabou (2002), which depends on a shifting parameter and another parameter corresponding to one minus the measure of residual income progression (Musgrave and Musgrave, 1976). The empirics of our model are discussed in section 3, while simulations of our third-best policy scenarios are presented in sections 4 and 5.

2.1. Household utility

The economy is populated by H groups of households and each household in a particular group is the same type. Households in group h derive utility from consumption, z_h, and disutility from labour, l_h. Let $\vec{x}_h$ be the I-dimensional vector with the demands for consumption goods and $\vec{q}_h$ the corresponding vector of consumer prices faced by household h. Total consumer expenditures by a household of type h are $z_h \equiv \vec{q}_h{}'\vec{x}_h$ which provides it with indirect utility $v_h(\vec{q}_h, z_h)$. Total utility for the household of type h is

$$(1) \qquad V_h = v_h(\vec{q}_h, z_h) - \varphi_h \frac{l_h^{1+1/\varepsilon_h}}{1+1/\varepsilon_h},$$

where the Frischian wage elasticity is $\varepsilon_h > 0$ and the disutility cost of labour parameter is $\varphi_h > 0$. Labour supply enters utility in weakly separable fashion.[7]

Household h receives a gross wage W_h and exogenous income $\overline{z}_h$ and benefits from applicable tax deductibles δ_h.[8] It may also receive an untaxed climate dividend (uniform, non-individualised lump-sum transfer) s_h from the government. Income is spent on taxes $T_h = \boldsymbol{T}(W_h l_h + \overline{z}_h - \delta_h)$, where $\boldsymbol{T}(.)$ denotes the general income tax schedule. Disposable income is spent on consumption and exogenous saving, σ_h, so the budget constraint is

$$(2) \qquad z_h = \vec{q}_h'\vec{x}_h \;=\; W_h l_h + \overline{z}_h - \boldsymbol{T}(W_h l_h + \overline{z}_h - \delta_h) + s_h - \sigma_h.$$

2.2. Commodity demand and indirect utility

Households take taxes, transfers, and aggregate emissions as exogenous. Roy's identity gives the uncompensated Marshallian demands in terms of prices and total expenditure, $\vec{x}_h(\vec{q}_h, z_h) = -\left[\frac{\partial v_h(\vec{q}_h, z_h)}{\partial \vec{q}_h}\right] / \frac{\partial v_h(\vec{q}_h, z_h)}{\partial z_h}$. The inverse of the indirect utility function $v_h(\vec{q}_h, z_h)$, i.e. expenditure function $z_h = E_h(\vec{q}_h, v_h)$ yields, using Shephard's lemma, the compensated Hicksian demands in terms of prices and indirect utility, $\vec{x}_h^H(\vec{q}_h, v_h) \equiv \partial E_h(\vec{q}_h, v_h)/\partial \vec{q}_h$. The uncompensated price and total expenditure elasticities for good i are $\varepsilon_{ih}^q \equiv \left(\frac{q_{ih}}{x_{ih}}\right) \frac{\partial x_{ih}(\vec{q}_h, z_h)}{\partial q_{ih}}$ and $\varepsilon_{ih}^z \equiv \left(\frac{z_h}{x_{ih}}\right) \frac{\partial x_{ih}(\vec{q}_h, z_h)}{\partial z_h}$.[9] The compensated price elasticities

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[7] Hence, there are no cross-price effects in leisure demand. They would drive a wedge between the optimal carbon tax and the Pigouvian tax (Corlett and Hague, 1953; Wijkander, 1985). Uniform commodity taxation should not be used to optimally redistribute incomes if leisure is weakly separable from consumption goods in the utility function (Atkinson and Stiglitz, 1976). It is then optimal to use the carbon tax solely for internalising externalities, not for raising revenue or making the distribution more equal. Empirical evidence from the Almost Ideal Demand System with nonlinear Engel curves suggests that energy-intensive commodities are complements with leisure and that the second-best optimal gasoline tax is substantially higher than the Pigouvian tax (West and Williams, 2007).

[8] Transfers may differ across groups, and so may depend for example on whether the household works or is retired or is a single person or a married couple.

[9] Instead of the latter, we can allow for exogenous saving and specify the income elasticity $(z_h + \sigma_h)\varepsilon_{ih}^z / z_h$, where σ_h denotes exogenous saving (see equation (2) below).

are $\frac{q_{ih}}{x_{ih}}\frac{\partial x_{ih}^{H}(\vec{q}_h,\nu_h)}{\partial q_{ih}} < 0$. We derive consumer demands from the EASI demand system (Lewbel and Pendakur, 2009) and provide details on their functional form in Appendix A.

2.3. Income taxation and labour supply

Following the macroeconomic literature of income taxation (e.g. Benabou, 2002; Heathcote et al., 2014), we approximate the detailed tax code by

$$(3) \qquad \boldsymbol{T}(W_h l_h + \overline{z}_h - \delta_h) \cong W_h l_h + \overline{z}_h - \delta_h - \max\left[0, \lambda_0 (W_h l_h + \overline{z}_h - \delta_h)^{1-\lambda_1}\right],$$

where $\lambda_0 > 0$ is a shift parameter associated with raising disposable income and lowering the income tax, and $0 \leq \lambda_1$ indicates the progressivity of the income tax.[10] We restrict income taxes to be non-negative.[11]

The marginal and average income tax rates for households in group h are $t_h^M \equiv T'(W_h l_h + \overline{z}_h - \delta_h) = 1 - \lambda_0(1-\lambda_1)(W_h l_h + \overline{z}_h - \delta_h)^{-\lambda_1}$ and $t_h^A \equiv T_h/(W_h l_h + \overline{z}_h - \delta_h) = 1 - \lambda_0(W_h l_h + \overline{z}_h - \delta_h)^{-\lambda_1}$, respectively. The income tax schedule is linear if $\lambda_1 = 0$. If the marginal exceeds the average tax rate, the income tax system is progressive and the coefficient of residual income progression smaller than 1, $RIP_h \equiv \frac{1-t_h^M}{1-t_h^A} < 1$ (Musgrave and Musgrave, 1976).[12, 13] In our case, $RIP_h = 1 - \lambda_1$, and the tax system is progressive if $\lambda_1 < 1$. We proxy the baseline income tax schedule (3) by estimating λ_0 and λ_1 from the data. In our policy exercises, changes in λ_0 and λ_1 correspond to reforms of the income tax system which affect the level and progressivity of income taxes.

Maximising household utility (1) subject to the household budget constraint (2) and the income tax schedule (3) given $\vec{q}_h$, s_h, δ_h, and σ_h gives equilibrium labour supply,

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[10] In fact, the coded tax functions replace $W_h l_h + \overline{z}_h - \delta_h$ by $\frac{W_h l_h + \overline{z}_h - \delta_h}{status}$ where *status* is 1 for singles and 2 for couples which we assume to be married and to benefit from tax splitting.

[11] This is important when considering the effects of income tax reform on low-income households.

[12] Musgrave and Musgrave (1976) define the coefficient of residual income progression, RIP_h, as the percentage by which net income of a household of type h increases if gross income increases by 1%, hence a lower RIP_h implies a more progressive tax. Consider the linear non-graduated income tax $\boldsymbol{T}(W_h l_h + \overline{s}_h - \delta_h) = (W_h l_h + \overline{s}_h - \delta_h)t_h$, where t_h is the constant marginal tax rate. Hence, $RIP_h = \frac{[1-(1-\tau)t_h]}{[1-(1-\tau)t_h + s_h]} < 1$ provided $s_h > 0$ in which case the income tax system is progressive (with a higher marginal than average tax rate) in the sense of Musgrave and Musgrave (1976). The average income tax rate increases with income.

[13] In the U.S. a *graduated* income tax refers to when the *marginal* rate of income tax rises with income while a *progressive* income tax refers to when the *average* rate of income tax rises with income. The U.S. has a graduated income tax but not a progressive income tax. We refer to a progressive income tax if the marginal exceeds the average income tax rate and $RIP_h < 1$.

(4) $\quad l_h = \left(\frac{(1-t_h^M)W_h}{\varphi_h P_h^M}\right)^{\varepsilon_h},$

where $P_h^M \equiv \left(\frac{\partial v_h(\vec{q}_h, z_h)}{\partial z_h}\right)^{-1}$ denotes the marginal cost of utility (the inverse of the marginal utility of income; see expression (A6) in Appendix A). Labour supply thus increases in the after-tax marginal wage but drops in the marginal cost of utility and the disutility cost of labour. Since utility is quasi-linear, there are no income effects on labour supply and climate dividends have no direct impact on labour supply. An upward shift in income taxes (lower λ_0) and a more progressive income tax (higher λ_1) depress labour supply. A higher carbon tax raises consumer prices, cuts the real wage, and curbs labour supply.

2.4. Producer prices and emissions

We denote the price of good *i* before carbon taxes (including pre-existing consumer taxes) by p_{ih} so that $q_{ih} = p_{ih} + \tau e_{ih}$ for $i = 1, \ldots, I$, where $\tau > 0$ is a specific tax on carbon emissions and e_{ih} the emissions intensity of commodity i for a household in group h.[14] Firms operate under constant returns to scale. In the short run their output is proportional to labour. Hence, output of commodity i is $x_i = B_i\, l_i$, where B_i denotes productivity of labour and l_i labour employed. Firms receive output price p_i and incur cost of labour W, abatement, and carbon taxes. Following the integrated assessment model of Nordhaus (2017), the cost of abating a fraction a_i of emissions from product *i* is fraction $\kappa_0 {a_i}^{\kappa_1}$ of output with $\kappa_0 > 0$ and $\kappa_1 > 1$. Emission intensities are $e_i = (1 - a_i)\overline{e}_i$, where $\overline{e}_i$ is the exogenous emission intensity corresponding to zero abatement.

Firms pass the carbon tax on unabated emissions fully to the consumer.[15] The price charged to consumers is thus $q_i = p_i + \tau(1 - a_i)\overline{e}_i$. Firms maximise profits $q_i x_i - W l_i - \kappa_0 {a_i}^{\kappa_1} p_i x_i - \tau(1 - a_i)\overline{e}_i x_i$ subject to $x_i = B_i\, l_i$ and take the wage W and price q_i as given. Optimality conditions for labour and abatement give $W = p_i(1 - \kappa_{0i} {a_i}^{\kappa_{1i}})B_i$ and $\kappa_0 \kappa_1 {a_i}^{\kappa_1 - 1} p_i = \tau \overline{e}_i$. We calibrate $B_i = W^0/p_i^0$ from the baseline wage W^0 and price p_i^0,

[14] Prices are household-specific since they derive from more disaggregated commodity demands and each household consumes different baskets of consumption goods (see section 3.5).

[15] However, Ganapati et al. (2020) allow for imperfect competition and find that 70% of energy-driven changes in input costs in U.S. manufacturing are passed through to consumers in the short to medium run. As a result, the share of welfare costs for consumers is 25-75% lower (with producers bearing a larger part of the burden) than in models with perfect competition.

and endogenise the wage W.[16] The case of similar effects on non-wage market income is one of the robustness checks presented in Appendix D.

The abatement rate is $a_i = (\tau/\bar{\tau}_i)^{1/(\kappa_1-1)}$, where $\bar{\tau}_i \equiv \frac{\kappa_0\kappa_1 p_i}{\bar{e}_i} > 0$ denotes the price of the backstop that brings emissions to zero ($a_i = 1$). A higher carbon tax decreases wages uniformly. It also increases abatement and curbs emission intensities, as can be seen from

(5) $$e_i = \bar{e}_i\left[1 - \left(\frac{\tau}{\bar{\tau}_i}\right)^{1/(\kappa_1-1)}\right].$$

The population weight for the group of households h is denoted by N_h and normalised to satisfy $\sum_{h=1}^{H} N_h = 1$, where H again denotes the number of groups of households (with each household in a particular group of the same type). Aggregate carbon emissions are

(6) $$A \equiv \sum_{h=1}^{H} N_h \sum_{i=1}^{I} e_{hi} x_{hi}(\vec{q}_h, z_h).$$

Emissions A take account of emission intensities differing across households because their consumption baskets differ. Policymakers are concerned about aggregate emissions (see social welfare (9) below), but households treat pollution as an externality.

2.5. Government budget constraint and revenue recycling

The government sets income tax and carbon tax revenue to cover the public revenue requirement R and spending on climate dividends, so its budget constraint is

(7) $$\sum_{h=1}^{H} N_h\left[W_h l_h + \bar{z}_h - \lambda_0(W_h l_h + \bar{z}_h - \delta_h)^{1-\lambda_1}\right] + \tau A = R + \sum_{h=1}^{H} N_h s_h.$$

The government's policy instruments are the specific carbon tax, τ, the climate dividend (or rebated transfers), s_h, and the parameters of the income tax system, λ_0 and λ_1. We require all to be non-negative. We assume that climate dividends are the same for each group, $s_h = s$ for $h = 1, \dots, H$, so we consider the policy instruments $\Theta\{\tau, s, \lambda_0, \lambda_1\}$. We only consider income tax reforms that can be financed by the generated carbon tax revenue, so that aggregate expenditure on climate dividends must be non-negative and cannot exceed carbon tax revenue. Thus, our third-best policy reforms must satisfy the additional constraints:

(8) $$0 \leq \sum_{h=1}^{H} N_h s_h \leq \tau A \quad \text{and} \quad \tau \geq 0.$$

[16] Nordhaus' model has Cobb-Douglas technology, $Y = (1-\kappa_0 a^{\kappa_1}) A K^{\alpha} L^{1-\alpha}$ with $W = (1-\alpha)Y/L$ and inelastic labour supply. Note that this expression equals ours with $A = B_i$ and $\alpha = 0$. Revenue from unabated emissions is refunded as lump-sum transfers and does not matter, since that model has a representative household.

2.6. Social welfare

Social welfare is the weighted sum of private welfare minus the effect of global warming damages. That is, we consider the household net utility, $V_h - \psi_h A$, where ψ_h denotes the disutility cost of aggregate emissions to households in group h. Low-income households may suffer more from the impact of global warming than high-income households, so that the ψ_h may vary with h. We assume the damage coefficient captures global damages, but a selfish government could limit it to local or national damages. We define social welfare as:

$$(9) \qquad \Omega = \sum_{h=1}^{H} \omega_h N_h (V_h - \psi_h A)$$
$$= \underbrace{\sum_{h=1}^{H} \omega^U N_h V_h}_{\textbf{\textit{efficiency}}\ (\Omega_{\text{eff}})} + \underbrace{\sum_{h=1}^{H} (\omega_h - \omega^U) N_h V_h}_{\textbf{\textit{equity}}\ (\Omega_{\text{eq}})} + \underbrace{\sum_{h=1}^{H} -\omega_h N_h \psi_h A}_{\textbf{\textit{emissions}}\ (\Omega_{\text{em}})},$$

where V_h is private welfare from equation (1), $\omega_h \geq 0$ is the marginal Pareto weight of a household in group h, and ω^U the Utilitarian welfare weight (see below).[17] Abatement costs are included in wages, so they do not feature directly in social welfare. Our EASI preferences are approximately quasi-linear (Appendix C), so that all terms in (9) are approximately measured in Euros. We assume that the Pareto weights decline with total expenditures in the baseline: $\omega_h = \omega_0 (z_h^0 + \sigma_h)^{-\xi}$, where $\xi > 0$ is the coefficient of relative inequality aversion (Atkinson, 1970) and $(z_h^0 + \sigma_h)$ is baseline income without carbon taxes. The constant $\omega_0 > 0$ normalises $\sum_{h=1}^{H} \omega_h N_h = 1$. Utilitarian weights ($\omega^U = \omega_0$) correspond to $\xi = 0$ and maxi-min weights to $\xi \to \infty$.

The first term in (9), Ω_{eff}, is the *efficiency* component, i.e. the private utilitarian component of social welfare due to changes in the consumption bundle and labour supply. The second term in (9), Ω_{eq}, is the *equity* component which corrects the private component of social welfare to allow for social welfare weights (i.e. by taking the difference between actual welfare and utilitarian weights). The third term in (9) is the *emissions* component, Ω_{em}, or the social cost of aggregate emissions.

To analyse the effects of policies, we employ measures of private and public welfare analysis. Changes in pre- and post-policy household welfare are expressed in equivalent variations (EVs). Expenditure of household h for the baseline scenario with utility v_h^0 and zero carbon taxes and climate dividends ($\tau = s_h = 0, \lambda_0 = \lambda_0^0$, and $\lambda_1 = \lambda_1^0$) is $E_h(\vec{p}_h, v_h^0)$.

[17] The weights ω_h generalise the marginal social welfare weights derived from a more conventional social welfare function. In general, they may depend on individual characteristics or non-welfarist objectives such as fairness, hard work, or sacrifice (Saez and Stantcheva, 2016).

With policy package $\Theta\{\tau, s, \lambda_0, \lambda_1\}$ the utility level is v_h^1. The EV for a household in group h is evaluated at the prices before the policy package is implemented and is thus

$$(10) \quad EV_h \equiv E_h(\vec{p}_h, v_h^1) - E_h(\vec{p}_h, v_h^0).$$

The equivalent variation indicates how many Euros a household in group h is willing to accept instead of implementing the policy package Θ. If a household is worse off under the new policy, e.g. because the climate dividend is insufficient to compensate for price increases resulting from the carbon tax, the EV is negative. By examining EVs across households, we gain insights into the distributional impacts of a particular policy package. EVs exclude the effect of changes in labour supply. In Appendix E we propose an alternative welfare measure and show that the effect of changes in the disutility of labour supply is negligible.

The effects of policy on social welfare are captured by decomposing changes in social welfare relative to the baseline into the efficiency, equity, and emissions components: $\frac{\Omega-\Omega^0}{\Omega^0} = \frac{\Omega_{\text{eff}}-\Omega^0_{\text{eff}}}{\Omega^0} + \frac{\Omega_{\text{eq}}-\Omega^0_{\text{eq}}}{\Omega^0} + \frac{\Omega_{\text{em}}-\Omega^0_{\text{em}}}{\Omega^0}$.

2.7. Policy experiments and the marginal cost of public funds

The government chooses policy $\Theta\{\tau, s, \lambda_0, \lambda_1\}$ to maximise social welfare (9) subject to the government budget constraint (7), the constraint on the cost of climate dividends (8), the income tax system (3), the decentralised equilibrium conditions (i.e. the disaggregated demand functions and household budget constraint (2), labour supply (4), emission intensities (5), and aggregate emissions (6)). Due to quasi-linear preferences, the preference for redistribution is mostly driven by declining Pareto weights rather than declining marginal consumption utilities Still, the latter differ across households and affect redistribution. For future reference we define μ_h as the Lagrange multiplier on household h's budget constraint (2) measuring the social value of providing an extra Euro to households and the Pigouvian carbon tax, $\tau^P \equiv \sum_{h=1}^{H} \psi_h/\mu_h$, as the social marginal damage. The marginal cost of public funds of a policy instrument is the cost to households of raising an extra Euro of government funds using this instrument. With μ^p the Lagrange multiplier of the government budget constraint (7), we define the marginal cost of public funds as $MCPF \equiv \mu^p / \sum_{h=1}^{H} \mu_h$).[18] We consider three policy scenarios in which the government chooses $\Theta\{\tau, s, \lambda_0, \lambda_1\}$ as described above, subject to the following additional constraints on recycling carbon tax revenue:

(i) **Carbon tax and dividend**: a uniform climate dividend ($s_h = s > 0$) and no income tax reform (λ_0 and λ_1 fixed), or

(ii) **Third-best optimal**: a uniform climate dividend, s, and income tax reform by varying λ_0 and λ_1, or

(iii) **Carbon tax and income tax reform**: no climate dividend ($s_h = 0$) and income tax reform by varying λ_0 and λ_1 only.

In section 4, we compute these policy scenarios for damage coefficients, ψ_h, equivalent to social marginal damage of 0, 50, or 100 Euro/tCO_2 and various degrees of inequality aversion, ξ. To study policy trade-offs between emission cuts, efficiency, and equity and to see how inequality aversion affects policy, we evaluate outcomes using changes in the efficiency, equity, and green components of social welfare, disaggregated private welfare (via EVs), and public costs (via MCPFs).

3. Model estimation and calibration

We estimate commodity demand and labour supply using household incomes and expenditures provided in the German Survey of Incomes and Expenditure (EVS). We aggregate consumption into eight commodities (I = 8), i.e. food, heating (natural gas, liquid fuels, solid fuels), electricity, housing, transport (private and public transport and telecommunications), durables (small appliances, clothing, and shoes), services (education and health), and other consumption goods (recreation and culture, restaurants and hotels, and financial services). For the estimation of labour supply, we take marginal income tax rates from the German tax code. We then match consumption data with data on emissions provided to us at a high level of disaggregation for the year 2013 from Destatis (2019). Finally we calibrate firm abatement using the model DICE2016R (Nordhaus, 2017).

[18] Our definition of the MCPF also takes account of the social value of income changes (e.g. Slemrod and Yitzhaki, 2001; Jacobs and van der Ploeg, 2019). The marginal excess burden MEB is $MCPF$ – 1. If climate dividends can be set optimally, the socially-weighted sum of the marginal value of an extra Euro to each household must equal the marginal social value of an extra Euro to the government, i.e. $MCPF$ = 1. In practice, $MCPF \neq 1$ if non-distorting lump-sum finance of public spending is infeasible.

3.1. EASI demand system estimates

The EASI demand system offers more general functional forms than other demand systems. In Appendix B we present details of the estimation and descriptive statistics of the EVS data. These are briefly summarised in this section. Figure B1 plots Engel curves for our eight composite commodities. None of these are linear. Engel curves for food, housing, and carbon-intensive commodities (electricity, transport, and heating) rise and then flatten at higher total expenditures. In contrast, the Engel curve for services is mildly convex while those for others and durables are more linear. The plots of the budget shares of each good versus the log of aggregate expenditures are presented in Figure B2. Low-income households spend a larger proportion of their income on food, heating, electricity, housing, and transport than more affluent households. Hence, carbon taxes on these commodities are regressive. The opposite holds for the other categories. There are thus important differences in consumption patterns across expenditure (and income) levels, the correct modelling of which calls for the flexibility offered by the EASI demand system.

Table B2 presents estimates of the EASI demand system and Tables B3 and B4 give the uncompensated price elasticities for the first and fourth quartiles of household expenditure. The own price elasticities are less than one in absolute value for all commodities except for other commodities and services. Taxing these commodities, therefore, has relatively fewer efficiency losses. Furthermore, households that spend a relatively large amount on these commodities carry a disproportional burden of any tax. Elasticities for electricity, heating, and transportation for low-income households are slightly larger than for more affluent households in absolute terms. This indicates that, faced with higher price levels, vulnerable households can reduce their tax burden by reducing their consumption. The cross-price elasticities indicate that food, housing, electricity, and durable goods are complementary goods to electricity. Higher heating prices curb the demand for these commodities by high- and low-income households.

Table 1: Expenditure elasticities for first and fourth expenditure quartile (EASI)

	Food	Housing	Electricity	Heating	Transport	Service	Durable	Other
Δ% z	Δ% Q							
1st quartile	0.63***	0.49***	0.45***	0.58***	1.05***	1.82***	1.38***	1.84***
4th quartile	0.73***	0.49**	0.52***	0.77**	0.90**	1.74***	1.29***	1.59**

Significance levels: * p<0.10, ** p<0.05, *** p<0.01.

Table 1 presents the elasticities with respect to total expenditure. These indicate that food, housing, electricity, and heating are necessities. Taxing these commodities thus imposes a disproportional burden on vulnerable households. It also illustrates the difference in expenditure patterns across expenditure levels.

3.2. Estimation of labour supply

Our labour supply function depends on the behavioural responses implied by the consumer demand system via the marginal ideal cost-of-living index, obtained from our EASI demand system estimates. We use the Generalised Method of Moments to estimate a log-linearised version of the labour supply schedule:

(13) $\log(l_h) = \alpha_0 + \alpha_1 \log[(1 - t_h W_h)/P_h^M] + \alpha_{d1} d_{1h} + \alpha_{d2} d_{2h} + \ \dots,$

where the Frisch elasticity is $\varepsilon^F = \alpha_1$. Dummy variables, d_1, d_2, etc., capture differences in labour supply across household characteristics (see Table 2). The marginal disutility of labour in equation (1) for households of type 1 is $\psi_h = \mathrm{e}^{-\alpha_0/\alpha_1}\mathrm{e}^{-\alpha_{d1}/\alpha_1}$. Table 2 gives our reduced-form estimate of labour supply.[19] In our policy simulations we draw a random sample of 1,000 units from the 2013 EVS. The weights in the subsample are scaled to provide the aggregated values of the full EVS sample. Labour disutility is aggregated on an annual basis using sample population weights. Our estimates imply a higher Frischian wage elasticity of 0.615 than the central estimate of 0.4 of CBO (2012), a micro-econometric estimate.[20]

Table 2: Econometric estimate of the labour supply

	Log hours (EASI)
Frischian wage elasticity (ε^F)	0.615***
Disutility of labour (d_0), log	- 11.974***
Rural household dummy (d_1), log	- 0.065***
HH head male dummy (d_2), log	0.050***
Children present dummy (d_3), log	0.015
Single HH dummy (d_4), log	0.735***

Significance levels: * p<0.10, ** p<0.05, *** p<0.01.

[19] Our estimate of labour supply uses a subset of the EVS database, as data on worked hours is only provided for the survey years 2003, 2008, and 2013 (30,606 observations). We obtain separate estimates of labour disutility across household types by estimating α_0 for different household types using dummy variables. We also include in α_0 the coefficient of the inverse Mills ratio evaluated at the mean sample. We corrected the potential correlation between the error term and wages by using the mean of wages across different socio-economic categories as an instrumental variable (cf. West and Williams, 2007). In stage one, we estimate the probability of working, controlling for dependent children, household size, sex of the head of the household, and level of government transfers. In stage two, we estimate the labour supply function including the inverse Mill ratio (Heckman, 1979).

[20] This may be due to differences between Germany and the US, and micro estimates typically yield lower wage elasticities than the ones used in macro studies.

3.3. Income tax system

We use Loeffler et al. (2014) to calculate the German marginal income tax, which is zero for taxable incomes below € 8,354, then jumps to 14% and rises linearly to 24% for incomes of € 13,469. The marginal income tax rate continues to rise linearly to 42% for incomes below € 52,882, after which the marginal income tax is constant at 42% for incomes below € 250,730, and 45% for incomes above this threshold. Germany permits the practice of income splitting for married couples, where each spouse is taxed on half of joint income. We assume that households with two adults opt for joint taxation, and ignore poverty traps from child allowances and rent, and legal subsidies being targeted at low incomes. Our baseline function for average tax, $t_h^A = \max\big(0, 1 - \lambda_0 (W_h l_h + \overline{z}_h - \delta_h)^{-\lambda_1}\big)$, with $\lambda_0 = 4.503$ and $\lambda_1 = 0.166$ approximates average tax rates well for taxable incomes up to about € 150,000 per year.[21]

3.4. Carbon footprints

Carbon footprints, measured in $KgCO_2$ per Euro, are computed by combining information on emissions and expenditure on consumption goods.[22] Emissions data include direct (scope I) and indirect emissions (scope II), but not emissions abroad embodied in imported intermediate goods (scope III). The resulting absolute and relative emission intensities are reported in Table 3, using equivalence scales for households (cf. Pollak and Wales, 1981; Lewbel, 1989). While richer households have a larger carbon footprint, relative emissions intensity falls with income. Transferring one Euro from a poor to a rich household, thus, decreases total emissions.

[21] In our simulations, we approximate the maximum function using the Smooth Maximum Unit $\max(x, y) = (x + y)/2 + \sqrt{(x - y)^2 + \varepsilon}/2$ with $\varepsilon = 0.02$. Marginal income taxes are discontinuous at the point where the tax-free allowance, $a = \lambda_0^{-1/\lambda_1}$, is exhausted. We approximate this discontinuity by multiplying $t_h^M = 1 - \lambda_0 (1 - \lambda_1)(W_h l_h + \overline{z}_h - \delta_h)^{-\lambda_1}$ with the sigmoid indicator function $I(x) = 1/\big(1 + e^{-\varepsilon_1 \tanh(\varepsilon_2 (x - a))}\big)$, where x is annual taxable income adjusted for number of working adults, $\varepsilon_1 = 10$, and $\varepsilon_2 = 1/1000$.

[22] Emissions data is provided by the German Statistical Office and follows the COICOP (Classification of Individual Consumption According to Purpose) classification. We aggregate them into our eight types of commodities using the German Survey of Incomes and Expenditure (EVS) data for the year 2013, the latest wave for which we can match emissions with expenditure data. The data was provided to us at a high level of disaggregation for the year 2013 from Destatis (2019). Aggregated values for previous years are reported in Mayer and Flaschmann (2011).

Table 3: Emission intensities and emissions from quarterly consumption

	Food	Housing	Electricity	Heating	Transport	Service	Durables	Others
			CO2 emission intensity (kg CO2/€)					
1st Quartile	0.193	0.044	2.172	1.971	0.761	0.084	0.059	0.089
2nd Quartile	0.160	0.044	1.805	1.595	0.870	0.074	0.046	0.077
3rd Quartile	0.140	0.042	1.581	1.371	0.834	0.068	0.042	0.070
4th Quartile	0.128	0.040	1.440	1.254	0.808	0.069	0.036	0.069
			CO2 emissions (quarterly, tCO_2)					
1st Quartile	0.118	0.059	0.287	0.400	0.323	0.023	0.014	0.087
2nd Quartile	0.154	0.090	0.349	0.495	0.547	0.038	0.020	0.141
3rd Quartile	0.178	0.112	0.391	0.608	0.679	0.053	0.026	0.190
4th Quartile	0.212	0.133	0.433	0.860	0.930	0.113	0.039	0.333

Note: The quartiles of household consumption are scaled by household size using the equivalence scale.

3.5. Calibration of the abatement of emissions

We assume that firms abate emissions if it is cheaper than to pay the carbon price. The respective abatement cost function $\kappa_0 a^{\kappa_1}$ gives the cost (as percent of output) of mitigating a percent of emissions. We take this functional form, the backstop price for full abatement, $\bar{\tau}_i \equiv \frac{\kappa_0 \kappa_1 p_i}{\bar{e}_i} = €500/tCO_2$, and the elasticity, $\kappa_1 = 2.6$, from DICE-2016R (Nordhaus, 2017) and assume it is uniform across commodities. Since household consumption is aggregated into eight commodities in our empirical application, households face household-specific prices, p_{ih} and q_{ih}, and emission intensities, $\bar{e}_{ih}$ and e_{ih}. We average over households and goods to obtain $\kappa_0 = \frac{\bar{\tau}_i}{\kappa_1} \frac{1}{H} \frac{1}{I} \sum_h \sum_i \frac{\bar{e}_{hi}}{p_{hi}} = 0.1496$, which implies a cost of 14.96% for full abatement.[23] This compares with a cost of 7.4% for 2015 (and 6.7% for 2020) in DICE-2016R, which is a model of the global economy. The absolute value of the elasticity of emissions with respect to the carbon tax is $\frac{1}{\kappa_1 - 1} \frac{\tau}{e_i} \left(\frac{\tau}{\bar{\tau}_i}\right)^{1/(\kappa_1 - 1)}$ and is lower if κ_1 and thus $\bar{\tau}_i$ is higher.

4. Third-best optimal carbon taxes for three different recycling schemes

Policymakers need to balance trade-offs of equity, environment, and efficiency in implementing green tax reform. We present simulations for our three scenarios to dissect

[23] Alternatively, we might set $\bar{\tau}_i = \kappa_0 \kappa_1 \frac{1}{H} \frac{1}{I} \sum_h \sum_i \frac{p_{hi}}{\bar{e}_{hi}} = €500/tCO_2$ for all i in which case $\kappa_0 = 0.0224$ and emissions are very price-elastic.

these trade-offs and their relative importance for different values of the damage coefficient for global warming, ψ_h, which we assume is uniform across households, and the coefficient of relative inequality aversion, ξ. For our baseline value of inequality aversion we choose $\xi = 1.6$, which rationalises the existing German income tax schedule as welfare-maximising absent lump-sum transfers and climate damages and given the government's fixed revenue requirement.

Sections 4.1-4.3 discuss Figure 1, which plots the carbon tax, the climate dividend, and the income tax schedule for the three policy scenarios discussed in section 2.7 against inequality aversion (ranging from zero to 1.6), and for three damage coefficients calibrated to social marginal damages of €0 (blue dashed), €50 (green dotted), and €100 (violet solid) per ton of CO2, at zero inequality aversion. The case of zero damages ($\psi_h = 0$) allows us to identify Ramsey's motive for taxing carbon. The case of zero damages and a carbon tax set to zero is our before-policy baseline (grey lines in Figures 1 and 2). Section 4.4 discusses Figure 2, which plots the corresponding effects on total emissions, hours worked, and expenditure inequality.

Table 4: Baseline results for three different recycling scenarios with social marginal damages of €50/tCO_2 and €100/tCO_2 in brackets and a coefficient of relative inequality aversion of 1.6, percentages are relative to a no-damages and no-carbon-tax baseline.

Recycling scenario	(i) Carbon tax and dividend	(ii) Third-best optimal	(iii) Carbon tax and income tax reform
Carbon tax, €/tCO_2	51 (77)	87 (119)	12 (51)
Climate dividend, €/year	283 (341)	613 (732)	0 (0)
Emissions, %	-27 (-35)	-38 (-46)	-12 (-28)
Employment, %	-0.8 (-1.2)	-1.2 (-2.3)	-1.1 (-1.9)
Green gain, %	1.0 (2.6)	1.4 (3.4)	0.4 (2.1)
Efficiency gain, %	-1.0 (-1.9)	-2.0 (-3.7)	-0.8 (-2.0)
Equity gain, %	1.0 (1.5)	2.2 (3.6)	0.5 (0.8)
Total welfare gain, %	0.9 (2.1)	1.6 (3.3)	0.2 (0.9)

Note: The sum of green, efficiency, and equity gains can differ from total welfare gain due to rounding.

Before we discuss Figures 1 and 2, we present in Table 4 baseline results for social marginal damages of €50/tCO2 (and €100/tCO2 in brackets) and our baseline coefficient of inequality aversion of 1.6. Starting from our baseline with no carbon taxes and inequality aversion of 1.6, consider what happens if the government starts internalising damages of €50/tCO_2. The policy of taxing carbon while using distributing lump-sum proceeds that are not needed to fund the shortfall of public revenue (scenario (i)), sets a carbon tax of €51/tCO_2 and a climate dividend of €283 per year. It curbs emissions by 27% and employment by 0.8%. Social welfare increases by 0.9% relative to the baseline, which decomposes into 1% each for the green gain and the equity gain and a 1% efficiency loss.

Third-best optimal policy, which also allows for income tax reform (scenario (ii)), sets a much higher carbon tax of €87/tCO_2 and climate dividend of €613 per year and achieves higher welfare; a welfare gain of 1.6% of which 1.4% and 2.2% are the green and equity gains and 2.0% is the efficiency loss. Consequently, emissions fall by more (38% instead of 27%) and the employment drop is twice as large. When policymakers rule out climate dividends (scenario (iii)), the optimal carbon is only €12/tCO_2 so that emissions do not fall much. As a result, the social welfare increases by a mere 0.2%.

We think a damage coefficient of €100/tCO_2 is more reasonable (for which figures are given in brackets in Table 4). In this case, the third-best response (in scenario (ii)) is to have a carbon tax of €119/tCO_2 and a climate dividend of €732 per year. It yields emissions cuts of 46%, while employment falls by 2.3%. There is a green and equity gain of 3.4% and 3.6%, but an efficiency loss of 3.7%. Overall welfare thus increases by 3.3% relative to the baseline. The carbon tax consistently exceeds the social marginal damages of emitting one ton of carbon in the third-best optimal scenario (ii) irrespective of the value of the social damage, while this is only the case at the low social damage value of €50/tCO_2 in the carbon tax and dividend scenario (i).

4.1. A carbon tax and climate dividend scenario

Scenario (i), depicted in column 1 of Figure 1, calculates the constrained optimal carbon tax when all additional revenue, which is not needed to fund the shortfall of public revenue, is rebated as uniform climate dividends. Carbon taxes increase in aversion to inequality and climate damages. Interestingly, carbon is priced below the social marginal damage of emissions except at high degrees of inequality aversion and for low damages. For a damage coefficient of zero, the carbon tax is at its zero lower bound for low values of inequality aversion and becomes positive (and therefore above the social marginal damages) if inequality aversion is larger than 0.38. Following these carbon taxes, climate dividends rise with inequality aversion and the value of the damage coefficient. As we will see later, not all carbon tax revenue is rebated as part of it is needed to fund the public revenue shortfall resulting from the erosion of the income tax base, which stems from the policy-induced falls in the real consumption wage and employment. This effect is higher for higher damage coefficients.

4.2. Third-best optimal carbon taxation

Policymakers can improve the carbon tax/climate dividend policy by also reforming the income tax system as in the third-best optimal scenario (ii), which is depicted in column 2 in Figure 1. In this scenario, the government sets the optimal carbon tax (τ), the climate dividend (s), and the two parameters of the income tax system (λ_0 and λ_1)) subject to all the constraints discussed in section 2.7. This additional degree of freedom causes policymakers to set carbon taxes higher and hand out larger climate dividends than in scenario (i). At low levels of inequality aversion, the tax is 20% higher and this difference increases to 50% at $\xi = 1.6$. Interestingly, policymakers choose to fully compensate for the budgetary shortfall due to carbon pricing by increasing income taxes (i.e. holding overall income tax receipts constant, see also discussion in section 5). This ensures all lump-sum transfers of carbon tax revenue are at their maximum.

Using the extra public revenue to fund climate dividends alone mitigates adverse effects on equity but is costly since the negative effects of carbon taxation on the real consumer wage and labour supply cannot be mitigated. The inability to compensate for the negative impact of carbon taxation on income tax revenue thus lowers efficiency and raises the cost of redistribution. If income tax reform is permitted as well as handing out climate dividends, this adverse effect is mitigated by making the income tax system less progressive while holding total income tax receipts constant. Given our choice of the baseline value of $\xi = 1.6$, which rationalises the existing tax code (as it maximises welfare in the no-damage and no-carbon-tax baseline, which we depict in grey), the progressivity of the income tax remains practically unchanged from its baseline for this value of inequality aversion. With utilitarian welfare ($\xi = 0$), the policymaker places a higher weight on efficiency and reduces the progressivity of the income tax by shifting the burden of income taxation to lower incomes, eliminating the tax-free allowance, and lowering marginal income taxes (lowering λ_0 and λ_1). As a result, the income tax becomes nearly linear. (Figures C3 and C4 in Appendix C report equilibrium values of λ_0 and λ_1 across all values of ξ).

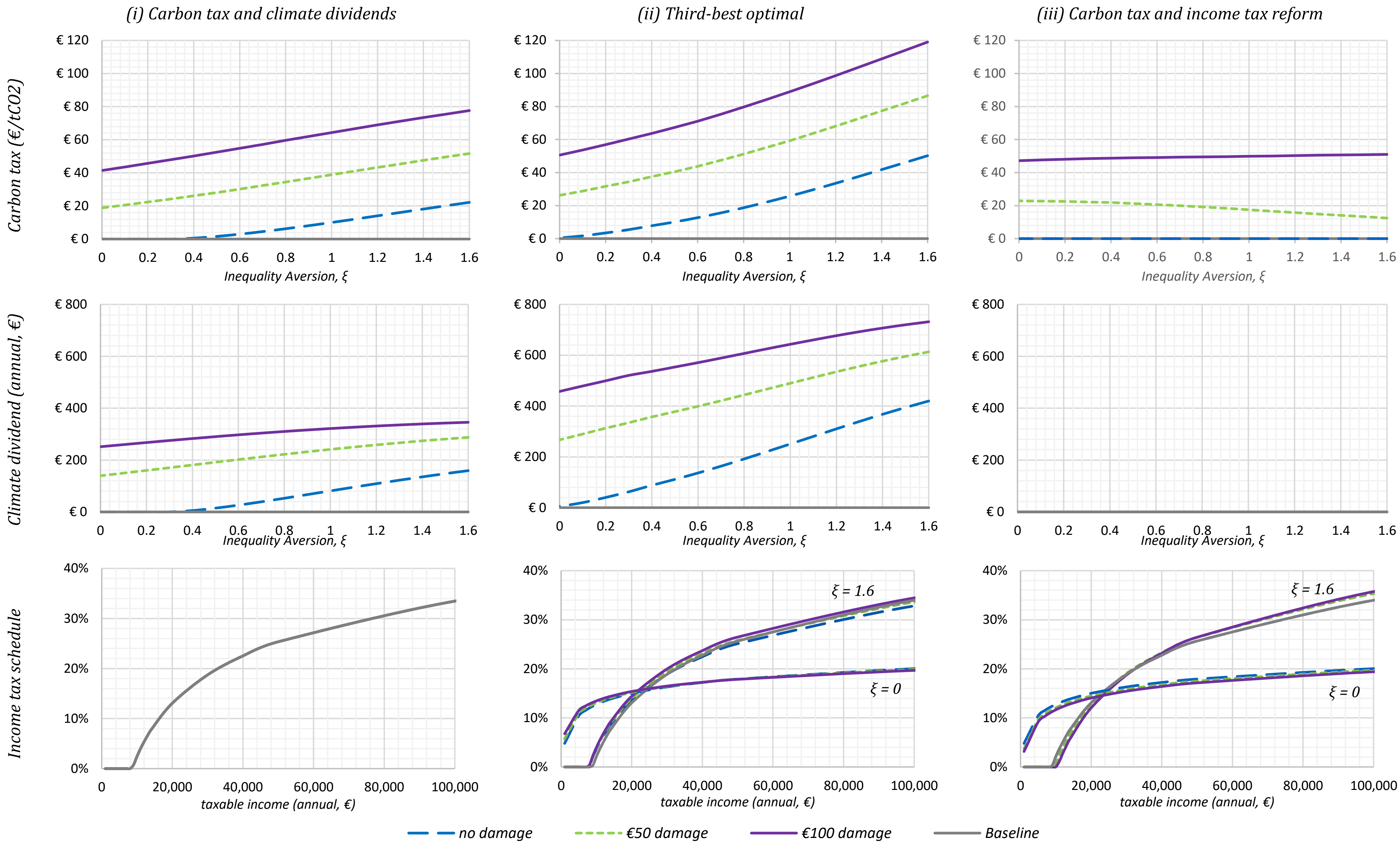


Figure 1: Optimal policy packages for various rates of social marginal damage, $\psi_h = \psi, \forall h$: (i) carbon taxes and climate dividends, (ii) third-best optimal, (iii) carbon taxes and income tax reform.

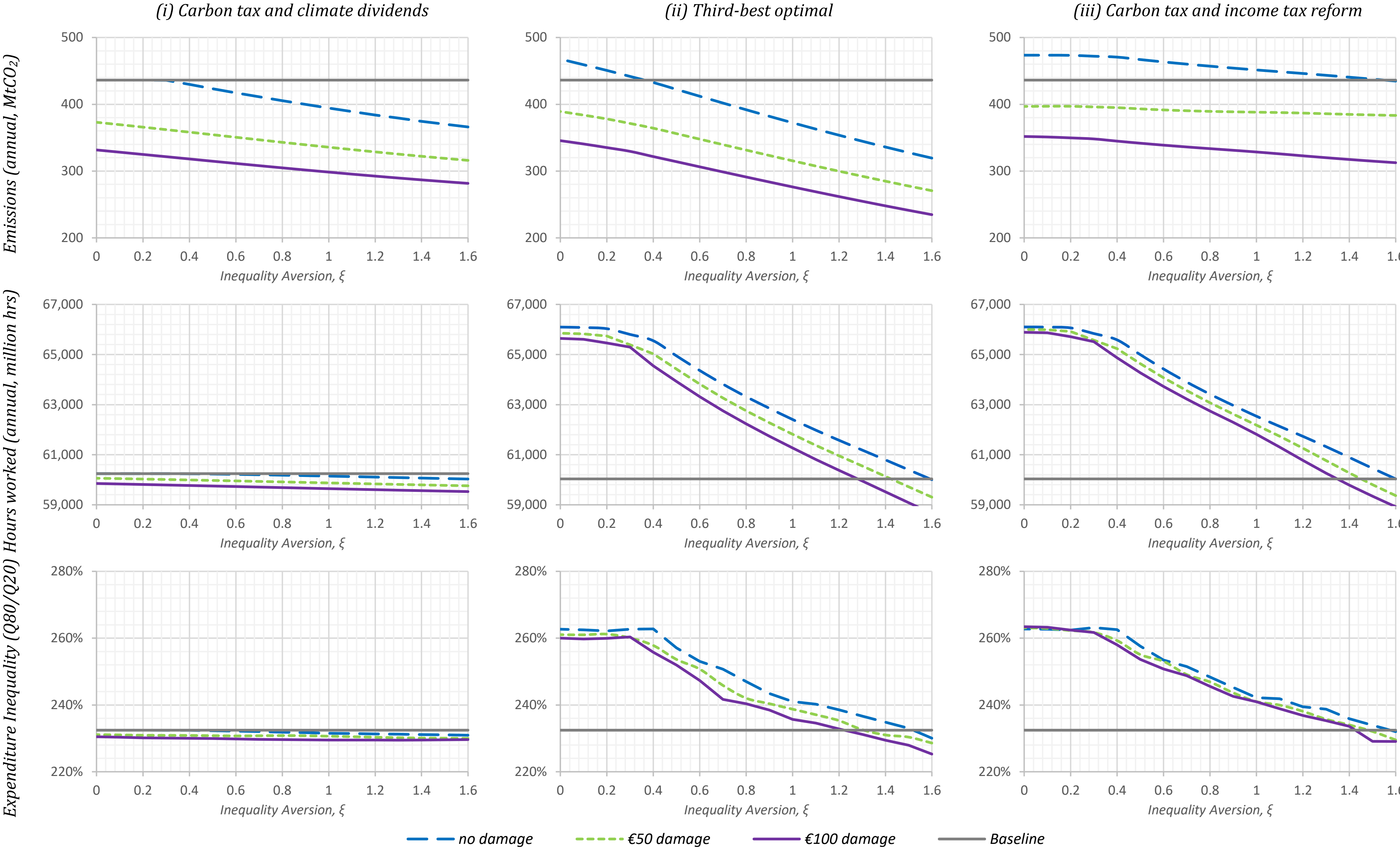


Figure 2: Effects of optimal policy packages on emissions, hours worked, and inequality for various rates of the social marginal damage coefficient, $\psi_h = \psi, \forall h$: (i) carbon taxes and climate dividends, (ii) third-best optimal, (iii) carbon taxes and income tax reform.

For the third-best optimal scenario (ii), we again see the pattern that carbon taxes and climate dividends increase with inequality aversion and the value of the social marginal damage. Higher carbon taxes (relative to scenario (i)) exceed the social marginal damages of emissions for a broader range of the coefficient of inequality aversion and damage levels. This may seem surprising due to the regressive nature of the carbon tax. However, the modest price elasticities of demand and supply of commodities indicate that carbon taxes are a relatively efficient way to raise carbon tax revenue. The carbon tax erodes the income tax base, unless its adverse effect on labour supply is mitigated via lower income taxes. If carbon tax revenue is recycled as climate dividends, then this does not happen and the distortion in labour supply is larger. Recycling only via climate dividends is therefore, less efficient but more equitable. Even without climate damages ($\psi_h = 0$) and, as such, a social marginal damage of €$0/tCO_2$, the carbon tax grows from €0 to €50 per ton of CO_2 as inequality aversion increases, which indicates its usefulness in raising public revenue and addressing income inequality despite its distortionary effects on labour supply and efficiency.

Summing up, third-best optimal climate policy in our model is geared more toward equity than efficiency. Climate policy is used to finance climate dividends while total income tax receipts are held at their baseline level, which is also their upper bound. This inability to raise income tax revenue for climate dividends or other lump-sum transfers leaves the carbon tax as the only means of raising public revenue. Efficiency concerns are addressed through budget-neutral income tax reform, e.g. by making the tax less regressive when the aversion to inequality falls.

4.3. A carbon tax for income tax reform

Here we study the case in which climate dividends cannot be handed out, the carbon tax and income tax reform scenario (iii). Carbon tax revenue must be recycled by reforming the income tax system, i.e., reducing income taxes or changing its progressivity. However, these reforms cannot benefit the lowest income earners since we restrict taxes to be non-negative. Our simulations show that the government only makes limited use of the carbon tax. While carbon taxes in this scenario are not very different from those of other scenarios at low levels of inequality aversion, they remain constant or fall slightly as inequality aversion increases.

Carbon tax revenue in this scenario is generally used to make the tax system slightly more progressive to offset the regressive effects of carbon taxation. At low values of inequality aversion, income taxes are less progressive and (more) evenly distributed. Income tax schedules mimic the third-best optimal scenario (ii) discussed in section 4.2.

The early "double dividend" literature (e.g. Bovenberg and de Mooij, 1994; Bovenberg and van der Ploeg, 1994, 1998ab; Goulder, 1995; Bovenberg, 1999) suggests that in typical distortionary tax systems the optimal carbon tax is below the social marginal damage, but in Figure 1, the optimal carbon tax might be above or below the marginal damage. To understand this, note that the optimal carbon tax is positive in scenarios (i) and (ii) even if the social marginal damage is zero, and especially so for higher degrees of inequality aversion. If one focuses on the difference between the optimal carbon tax for positive social marginal damages and the carbon tax for zero damages, the portion of the carbon tax that is due to inequality aversion is stripped out and the difference between the two carbon taxes is always less than the social marginal damage. One thus corrects for the optimal carbon tax being used to finance a higher climate dividend, if inequality aversion is high enough, and even if the marginal social damage is zero. This does not occur in scenario (iii), where climate dividends are ruled out.

4.4. Emissions, hours worked, and expenditure inequality for the three scenarios

Figure 2 presents aggregate effects (emissions, hours worked, and expenditure of the fourth over the first quintile) of our three policy scenarios (across columns). These measures capture, respectively, the environmental, efficiency, and equity targets of the government across various degrees of inequality aversion. As in Figure 1, we plot policy outcomes against the degree of inequality aversion for three levels of the global warming damage coefficient ψ_h. In general, for higher degrees of inequality aversion the government achieves higher equity, while lowering aggregate emissions but also sacrificing efficiency as hours worked decrease as well.

Aggregate emissions (top row) fall as carbon taxes rise (resulting from a higher global warming damage coefficient and, generally, from higher aversion to inequality) and rise as the income tax becomes less progressive and labour supply, income, and expenditure increase. Both effects are present in the third-best optimal scenario (middle column). The carbon tax effect dominates mostly, with the highest emissions reductions of 46% achieved under high environmental damages and high aversion to inequality aversion, thus again confirming the complementarity of environmental and equity objectives. Emissions reductions drop to 21% as inequality aversion falls to zero and carbon taxes are cut back from €119 to €51/tCO_2. Without environmental damages ($\psi_h = 0$) and low values of inequality aversion, the government imposes a zero or very low carbon tax and the effects of a less-progressive income tax schedule dominate. With higher incentives to work and incomes at the upper end of the income distribution, aggregate emissions increase beyond their baseline level.

The efficiency effects are summarised in the aggregate hours worked (second row). With baseline inequality aversion ($\xi = 1.6$) the third-best optimal policy scenario (ii) imposes virtually no change to the income tax code and the efficiency-reducing effects of the carbon tax dominate. Hours worked decrease as prices rise and nominal wages fall. As inequality aversion falls, the income tax code becomes less progressive and aggregate hours worked increase. Our inequality measure, the ratio of the 80th percentile's expenditure over the 20th's one (third row), has a baseline value of 232%, with slightly lower values at high values of inequality aversion and values up to 261% with zero inequality aversion, as the government prioritises efficiency over equity.

The other two scenarios have only one of the two revenue recycling options. In the carbon tax and climate dividend scenario (left column), climate policy's effects of higher prices and lower wages cannot be offset using income tax reform. Aggregate emissions, aggregate hours worked, and inequality always fall slightly relative to baseline. In the carbon tax and income tax reform scenario (right column) total emissions reductions are smallest, while changes in hours worked and the income distribution do not differ much from the third-best optimal scenario (ii). Here the case without damages (and a carbon tax) is most interesting as it isolates the effect of income tax reform. The similarity in efficiency and equity to the third-best scenario (ii) suggests that revenue-neutral income tax reform is the driving force behind these changes.

5. Welfare effects and public costs

Here, we discuss the public and private welfare costs of our three policy scenarios, using the welfare measures and the marginal cost of public funds in sections 2.6 and 2.7. Before we do so, Table 5 reports the sources and uses of public funds for our three recycling scenarios for two different values of inequality aversion and social marginal damages of €100/tCO2. In the carbon tax and climate dividend scenario (i) income taxes cannot be adjusted and some of the carbon tax revenue must be used to cover the policy-induced shortfall in income taxes. Table 5 shows that this effect is sizable with only 60-70% of carbon revenue available for disbursal.

Table 5: Sources and uses of government funds across the three policy scenarios for selected values of inequality aversion and a social marginal damage of €100/tCO_2

	ξ	Dividend	Carbon tax revenue	Dividend, as % of carbon tax revenue	Income tax revenue
(i) Carbon tax and dividend	0	€ 249	€ 356	70%	€ 7,442
	1.6	€ 341	€ 568	60%	€ 7,324
(ii) Third-best optimal	0	€ 458	€ 458	100%	€ 7,550
	1.6	€ 732	€ 732	100%	€ 7,550
(iii) Carbon tax and income tax reform	0	€ 0	€ 435	0%	€ 7,116
	1.6	€ 0	€ 417	0%	€ 7,133

Note: Dividend and carbon tax revenue are annual and per household to facilitate comparison between carbon tax revenue and dividend disbursal to households. Note that government expenditure per household and per year is set at € 7,550.

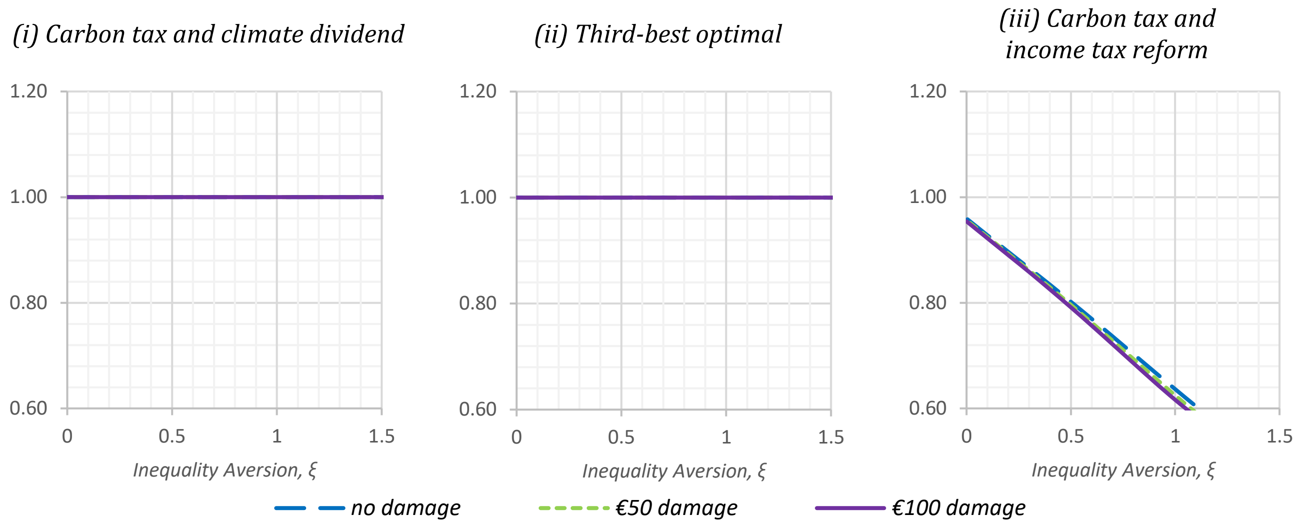
This fraction falls in the carbon tax, implying convex efficiency losses. In our preferred third-best optimal scenario (ii) the government always raises income taxes to its public expenditure requirement and distributes all carbon tax revenue as climate dividends. In the carbon tax and income tax reform scenario (iii) all of carbon tax revenue is used for income tax reform by definition. We include it in Table 5 for completeness.

5.1. The MCPF under the various model of recycling carbon tax revenue

The *MCPF* is a measure of the welfare cost of transferring an extra Euro from households to the government, i.e. it is the ratio of social welfare gained by one extra Euro in public funds divided by the social welfare cost of taking that Euro from households. For example, a *MCPF* of 1.2 implies that for every Euro raised, social welfare falls by 0.2 Euros. If optimal policy includes climate dividends (scenario (i)), the *MCPF* equal 1 as raising marginal revenue is then non-distortionary (even though the income tax system is not optimised). If $MCPF > 1$, this indicates that social welfare decreases if more revenue is raised. If $MCPF < 1$, social welfare increases if more revenue is raised.

Figure 3 plots the *MCPF*s for our three policy scenarios and, again, for three values of the global warming damage coefficient, ψ_h. With non-distortionary transfers available, the *MCPF* is equal to 1 when the climate dividend is part of the instrument mix, irrespective of whether income tax reform is implemented (scenarios (i) and (ii)). However, if climate dividends are infeasible and the government optimally chooses carbon taxes and income tax reform (scenario (iii)), the government relies solely on distortionary income and carbon taxes to raise public revenue. The *MCPF* is below one in this scenario irrespective of the global warming damage coefficient, because (if permitted) the government would want to raise welfare by increasing income taxes to fund lump-sum transfers. As aversion to inequality, ξ, increases, equity becomes more important to the government and the MCPF falls further, implying higher welfare gains from raising and redistributing income taxes.

Figure 3: MCPF across policy packages and rates of inequality aversion for various social marginal damage coefficients: (i) carbon taxes and climate dividends, (ii) third-best optimal, (iii) carbon taxes and income tax reform



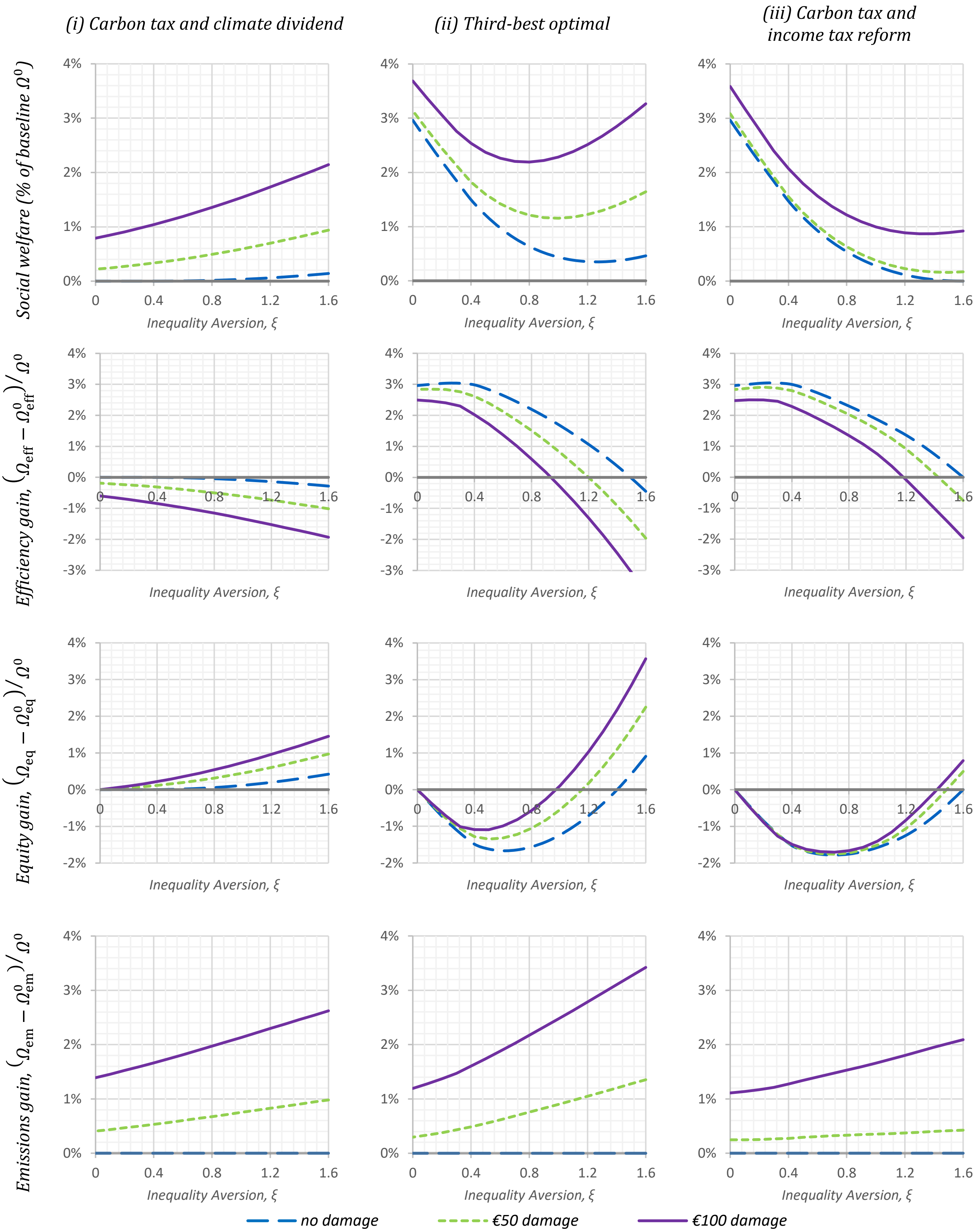
5.2. Aggregate and disaggregated welfare effects

Aggregate social welfare (9) in our model has components relating to efficiency, the environment, and equity. Households' welfare only captures utility from consumption and disutility from labour. Using equivalent variations (10), we contrast aggregate welfare outcomes with the individual household's welfare.

Decomposing changes in social welfare into efficiency, equity, and green gains

Table 4 presented the effects on social welfare relative to baseline for our three recycling scenarios and three different values of environmental damages with inequality aversion equal to the baseline value of 1.6. Figure 4 does the same for different degrees of inequality aversion. Given that the same allocation gives different welfare outcomes as welfare weights and environmental damage vary, we normalise welfare outcomes by baseline welfare conditional on a specific value of inequality aversion and environmental damage. Hence, the benefits of policy are highest if environmental damage is highest.

Figure 4: Social welfare across policy packages and rates of inequality aversion relative to baseline and for various rates of social marginal damage coefficients



If inequality aversion is zero, policymakers only trade off efficiency gains, Ω_{eff}, and emissions gains, Ω_{em}. The equity gain, Ω_{eq}, in equation (9) is for this case, of course, zero. As inequality aversion increases, equity concerns start to matter. In our preferred third-best optimal scenario (ii), where both income tax reform and climate dividends are feasible, these are, however, initially not large enough to offset gains from efficiency. The policymaker accepts losses in the equity gain, Ω_{eq}, to obtain efficiency and green gains. Policy only shifts towards redistribution, sacrificing efficiency, once inequality aversion is sufficiently high. Aggregate social welfare gains are highest if the policymaker focuses on either efficiency (gaining up to 3.7%) or equity (gaining of up to 3.3%), and lowest at intermediate values where none of the efficiency, equity, or green concerns are dominant. Since climate dividends are only funded via carbon taxes, the lower damage coefficient, ψ_h, and lower carbon taxes translate into lower social welfare gains.

Our other two scenarios, again, dissect these effects clearly. In scenario (i) where carbon tax revenue is used to fund climate dividends and make up for public revenue shortfalls, carbon taxes and climate dividends necessarily rise with the concern for inequality. Since the income tax system is unchanged, the efficiency gains are always negative with losses rising in level of damages and the associated carbon taxes. Using only climate dividends always leads to equity gains in Figure 4, which increase with inequality aversion and damage levels. Efficiency losses and equity gains are similar in magnitude and aggregate social welfare gains are mostly driven by the green welfare gains, which rise in the carbon tax. With no environmental damages, carbon taxes are very small, increasing to at most €22/tCO2, and welfare benefits range between 0-0.1%. With high environmental damages, carbon taxes reach up to €77/tCO2 and welfare gains rise to 2.1% relative to baseline welfare.

If the policymaker only sets carbon taxes and reform the income tax system, our scenario (iii), carbon and income taxes are very similar to those in the third-best optimal scenario (ii) for values of inequality aversion close to zero. The inability to disburse climate dividends in this scenario does not matter for welfare, as the equity component is close to zero when welfare weights do not differ much from the utilitarian case. If the policymaker is more averse to inequality, the equity gains become more important. Since lump-sum payments are not permitted in this scenario, equity losses cannot be mitigated; and the policy features lower carbon taxes and higher efficiency gains to realise welfare gains relative to the baseline. While similar in magnitude to those of the third-best optimal scenario (ii) at low values of inequality aversion, welfare gains fall steadily to around 1% with high damages and zero with low damages.

Summing up, the bottom row in Figure 4 shows that the green gain is highest with both a climate dividend and income tax reform, but a little less if there is no income tax reform; or even worse, if there is no climate dividend. Green and equity gains run in parallel as they both increase with the degree of inequality aversion. Efficiency gains fall with inequality aversion except for at low degrees of inequality aversion. So, green gains rise while efficiency gains drop with inequality aversion. Furthermore, green gains are higher, but efficiency gains are lower for higher damages. Not reforming the income tax system leads to efficiency losses.

The introduction of carbon taxes always yields green welfare gains. Similarly, there is always an efficiency loss if the income tax cannot be reformed (scenario (i)). Only in the third-best optimal scenario (ii), and if inequality aversion is high enough but not too high, improvements in all three welfare components are possible.

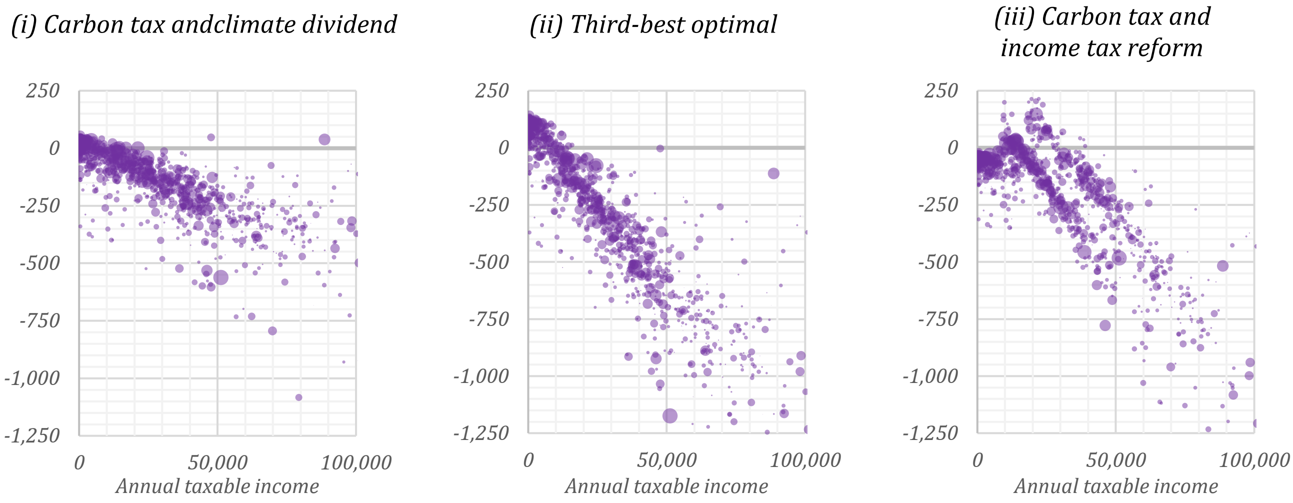
Effects on the welfare of individual households: equivalent variations

Figure 5 disaggregates social welfare by plotting policy-induced changes in household welfare using equivalent variations (10). The EVs include the costs of carbon taxation via price changes but not via the changes in labour supply or the benefits of avoided environmental damage (see Appendix E for details and an alternative welfare measure capable of accounting for both). Consequently, most households are worse off in any policy scenario. Low-income households benefit if climate dividends are available. In our preferred third-best optimal scenario (ii), income tax reform is also available which makes the distribution of policy costs even more progressive.

In the carbon tax and dividend scenario (i) some of the carbon tax receipts must be used to cover shortfalls in the public spending requirement, thus lowering the benefits for low-income households but increasing the burden on middle- and high-income households.

In the absence of climate dividends, households with income below the tax-free allowance necessarily have lower welfare, as they are faced with higher prices but cannot be compensated. In this carbon tax and income tax reform scenario (iii), the government chooses to distribute the income taxes so that middle-income rather than higher-income households benefit. This reflects the high degree of inequality aversion underlying the simulations of Figure 4. With zero inequality aversion (not depicted), efficiency concerns dominate and the gains of policy reform are shifted to high-income earners.

Figure 5: Equivalent variations Household-level effects of policy with inequality aversion equal to $\xi = 1.6$ and social marginal damages equal to €100/tCO_2 for scenarios (i) carbon taxes and climate dividends, (ii) third-best optimal, (iii) carbon taxes and income tax reform. Point size represents relative size of household in the population. EVs do not account for changes in aggregate emissions and damages.



6. Robustness

The distributional burden of carbon taxation across the income distribution depends on its direct effects (via changes in goods prices) and its indirect effects (via changes in factor prices). The focus of our model lies firmly on the former, while we also capture some supply-side effects on prices and emissions in section 2.4. In this section, we summarise the results presented in the Appendix D and F on robustness. Appendix D considers two indirect effects of carbon prices highlighted in previous studies for the United States: the endogeneity of capital income and the indexation of public transfers (Rausch et al., 2011; Fullerton et al., 2012; Williams et al., 2015; Cronin et al., 2019). So far, we have assumed that both capital income and transfers are fixed. In Appendix D we test whether the omission of the indirect effects introduces a systemic regressivity bias in incidence of carbon taxation. In Appendix F we re-estimate our model under a Linear Expenditure instead of an EASI demand system to test the relevance of non-linear Engel curves for third-best optimal carbon taxation.

In Appendix D we adopt the assumptions (i) that the effect of carbon pricing on capital income is the same as on wage income, thereby introducing an additional cost component of climate policy, and (ii) that public transfers are indexed to overall price inflation, thereby earmarking some of carbon tax revenue to cover the additional public expenditure. We present simulation results for three robustness cases (Endogenous capital income, CPI-adjustment of welfare transfers, and Endogenous capital income & CPI-adjustment of welfare transfers) and compare them with our baseline for all policy scenarios (Carbon tax and climate dividend, Third-best optimal, and Carbon tax and income tax reform). Figures D1-D3 present policy instruments; Figure D4 presents household-level equivalent variations (EVs) resulting from these policies across all three robustness cases and the baseline case.

We find that the introduction of negative effects of climate policy on capital income lowers carbon taxes by about 20% (relative to baseline). CPI-indexation of welfare transfers lower carbon taxes by at most €5 and higher levels of inequality aversion have higher reductions in the carbon tax. Lower carbon taxes and earmarking of revenue for CPI indexation lead to lower climate dividend payments. The effects on income taxes are insignificant across all robustness cases and policy scenarios. The only exception occurs under CPI-indexation of transfers in the carbon tax and income tax reform scenario (iii). Here carbon taxes increase significantly at high levels of inequality aversion relative to baseline. Since CPI indexation indirectly recycles some revenue as transfers, carbon taxes levels approach those of the carbon tax and dividends only scenario (i). Despite varying policy adjustments, the overall effects on household welfare remain similar across all robustness cases. Again, the significant change in policy in the carbon tax and income tax reform scenario (iii) in the "CPI-adjustment of welfare transfers" case translates into significant shifts in the distributional burden. Relative to baseline, lower-income households are significantly better off due to CPI-indexation, while all other households are worse off. Importantly, our findings appear robust and we cannot detect a systemic bias in the distributional burden of carbon taxation in our results. While the magnitudes of each policy instrument differ across robustness cases, their common features are consistent across policy scenarios.

We explore in Appendix F the same issues as in sections 4 and 5 with a Linear Expenditure instead of an EASI demand system, both estimated from the same data. Although the qualitative insights are similar, there are some important differences. First, in scenario (i) the carbon tax is set to zero when damages are zero under LES, but is positive under the EASI demand system for intermediate and high levels of inequality aversion. This has to do with the nonlinearity of the Engel curves in the EASI demand system. Second, in scenarios (ii) and (iii), income taxes are linear for utilitarian welfare ($\xi = 0$) under the LES, while under the EASI demand system they are progressive. We also present quantitative differences between the EASI and LES demand systems. Carbon taxes are set consistently slightly lower under EASI than under LES, except in the carbon tax and climate dividends scenario (i) with zero damages described above. Differences across demands range between €0 and €4 and increase in the aversion to income inequality. We find significantly larger differences in carbon taxation across the LES and EASI demand systems, with carbon taxes under LES up to three times those under EASI when firms cannot internalise and abate emissions (i.e. the backstop technology is prohibitively large, $\bar{\tau} \gg \tau$, or $\kappa_1 = 1$).

7. Concluding remarks

Implementing carbon taxes is dangerous for politicians, because large parts of the electorate worry the taxes will harm them and those less able to cope with price increases. Using a simulation model of the German economy with heterogeneous households, we offer new insights on how carbon taxation affects households across the income distribution and how the policymaker would want to use the carbon tax instrument and the revenue that it generates. In our optimising model, and subject to the constraints that we impose, we find that carbon taxes should be used to raise revenue and distribute climate dividends rather than to lower income taxes and boost efficiency. Total income tax receipts are raised to their upper bound (i.e. their baseline level), so that income tax reform is budgetary-neutral. The inability to raise income tax revenue leaves the carbon tax as the only means of raising public revenue. The carbon tax is set below (above) the social marginal damage of emissions at low (high) degrees of inequality aversion. Aggregate emissions, hours worked, and inequality decline with inequality aversion. Higher equity and lower aggregate emissions are achieved at the expense of lower efficiency and lower hours worked. Lower incomes are then better off while higher incomes are worse off.

If reform of the income tax system is infeasible and all carbon tax revenue is recycled as climate dividends, part of the revenue must be used to make up for the lower revenue from income taxes. The optimal carbon tax and climate dividend are lower than if revenue is also used to reform the income tax system for all degrees of inequality aversion. The inability to compensate for the negative impact of carbon taxation on income tax revenue lowers efficiency and raises the cost of redistribution. Without the efficiency boost of lower income taxes, aggregate emissions always fall. The efficiency losses in this scenario are small. The adverse welfare effects for higher-income individuals are smaller.

If the carbon tax revenue can only be used to reform the income tax system, the carbon tax is set lower and does not rise much as the degree of inequality aversion increases. More inequality aversion implies that a greater proportion of carbon tax revenue is used for climate dividends than reforming the income tax system. For low degrees of inequality aversion, income taxes are less progressive and (more) evenly distributed. Aggregate emissions reductions are smaller in the other two scenarios, while changes in hours worked and the income distribution are like those in the optimal scenario in which carbon taxes are complemented with both climate dividends and a less progressive income tax system.

In our baseline case (with inequality aversion ξ equal to 1.6) the third-best optimal policy sets carbon taxes above the social marginal damages of emissions and distributes all of carbon tax revenue as climate dividends. With a reasonable damage cost of €$100/tCO_2$, the optimal response is to have a carbon tax of €$119/tCO_2$ and a climate dividend of €732 per year. This yields emissions cuts of 46% and a drop in employment of 2.3%. The green and equity gains of 3.4% and 3.6% are partially offset by an efficiency loss of 3.7%, so overall welfare rises by 3.3% relative to when damages are not internalised. Our qualitative and quantitative insights regarding the efficiency and equity aspects of carbon taxes are derived for Germany. It remains to be seen whether they hold for other countries.

Future research may consider the following avenues of research. First, by departing from quasi-linear utility, one can allow for income effects in labour supply which would cause climate dividends to effect increased erosion of the income tax base. Second, by allowing for more detailed welfare payments, governments can choose to index welfare payments to soften the bite of carbon price increases at the lower end of the income distribution. Third, by taking into account dynamic aspects and general equilibrium effects of carbon taxation, one can allow for the intertemporal efficiency and equity effects (e.g. Barrage, 2019; Fried et al., 2021; Douenne et al, 2022; Benmir and Roman, 2023). Finally, governments might not be faced with the cool-blooded agents that we have assumed, but instead with (as protests about rising fuel prices demonstrate) people who perceive an increase in carbon taxes and consumer prices much more intensely than they do a cut in the income tax. The introduction of such misperceptions and other behavioural biases revises downward Pigouvian taxes (Farhi and Gabaix, 2020) and imposes additional constraints on the feasibility of carbon pricing, which must be taken up in future research.

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Appendix A: The EASI disaggregated demand system

The EASI demand system (Lewbel and Pendakur, 2009) postulates the log of indirect utility of household *h*, $\log v_h(\vec{q}_h, z_h)$, to be

$$\text{(A1)} \quad \log(v_h) = \log(z_h) - \sum_{j=1}^{I} w_{hj} \log(q_{hj}) + \frac{1}{2}\sum_{i=1}^{I}\sum_{j=1}^{I} a_{ij} \log(q_{hi}) \log(q_{hj}),$$

where the a_{ij} are the estimated compensated price effects in commodity demand. Using Roy's identity, this leads to the optimal budget shares for the different commodities as a function of indirect utility, and prices,

$$\text{(A2)} \quad w_{hi} = \sum_{r=0}^{R} b_{ir} \log(v_h)^r + \sum_{j=1}^{I} a_{ij} \log(q_{hi}) + \sum_{k=1}^{K} \left[d_{ik} \vartheta_{hk} \log(v_h) + g_{ik} \vartheta_{hk} \right],$$

where $w_{hi} \equiv q_{hi} x_{hi} / z_h$ and ϑ_{hk} are, respectively, the budget share of commodity *i* and household type *k* for a household in group *h*. Note that we have added to (A2) *r*-th order polynomials in log utility and extra explanatory terms for the *K* household types (not in (A1)) to get a better empirical fit. Equations (A2) are homogenous of degree zero in prices, so that only *I* – 1 budget shares need to be estimated. Substituting (A1) into (A2) yields an indirect system for the budget shares

$$\text{(A3)} \quad \begin{aligned} w_{hi} = b_{i0} &+ \sum_{r=1}^{R} b_{ir} \left[\log(z_h) - \sum_{j=1}^{I} w_{hj} \log(q_{hj}) + \frac{1}{2}\sum_{j=1}^{I}\sum_{j'=1}^{I} a_{jj'} \log(q_{hj}) \log(q_{hj'}) \right]^r + \sum_{j=1}^{I} a_{ij} \log(q_{hi} / q_{hj}) \\ &+ \sum_{k=1}^{K} d_{ik} \vartheta_{hk} \left[\log(z_h) - \sum_{j=1}^{I} w_{hj} \log(q_{hj}) + \frac{1}{2}\sum_{j=1}^{I}\sum_{j'=1}^{I} a_{jj'} \log(q_{hj}) \log(q_{hj'}) \right] + \sum_{k=1}^{K} g_{ik} \vartheta_{hk}. \end{aligned}$$

This system can be solved for the budget shares as functions of total expenditure z_h and prices q_{hj} (and of household attributes and the estimated coefficients of the EASI system). The EASI demand system allows for non-homothetic preferences and nonlinear Engel curves. Engel curves can be concave or convex and can slope down and/or upwards. Since budget shares add up to one, $\sum_{i=0}^{I} w_{hi} = 1$, and Slutsky symmetry must hold, we have

$$\text{(A4)} \quad \begin{aligned} &\sum_{i=1}^{I} b_{i0} = 1, \quad \sum_{i=1}^{I}\sum_{k=1}^{K} g_{ik} = 0, \quad \sum_{i=1}^{I}\sum_{k=1}^{K} d_{ik} = 0, \quad \sum_{i=1}^{I}\sum_{r=1}^{R} b_{ir} = 0, \\ &\qquad a_{ij} = a_{ji} \text{ and } \sum_{j=1}^{I} a_{ij} = 0, \; i = 1,..,I. \end{aligned}$$

Thus we estimate the $I-1$ budget share equations for the commodities and impose the $I(I-1)/2$ symmetry conditions. Demand for commodity I then follows residually.

The unit-expenditure function or ideal cost-of-living index for the EASI demand system is

$$\text{(A5)} \quad P_h^A \equiv \frac{z_h}{v_h} = \left(\prod_{i=1}^{I} q_{hi}^{w_{hi}}\right) e^{-\frac{1}{2}\sum_{i=1}^{I}\sum_{j=1}^{I} a_{ij}\log(q_{hi})\log(q_{hj})}.$$

If the a_{ij} are zero and budget shares are constant, we have Cobb-Douglas preferences with $P_h^A = \prod_{i=1}^{I} q_{hi}^{w_{hi}}$. Generally, this index is *implicitly* defined due to the presence of the w_{hi} which requires substitution of (A2) or (A3). From equation (A2) we obtain the expression $\frac{\partial w_{hi}}{\partial z_h} = \left[\sum_{r=1}^{R} b_{ir} r \log(v_h)^{r-1} + \sum_{k=1}^{K} d_{ik}\vartheta_{hk}\right]\frac{d\log(v_h)}{dz_h}$ and from equation (A1) we obtain

$$\frac{d\log(v_h)}{dz_h} = \frac{1}{y_h} - \sum_{j=1}^{I}\log(q_{hj})\frac{\partial w_{hj}}{\partial z_h} = \frac{1}{z_h} - \left(\sum_{j=1}^{I}\log(q_{hj})\left[\sum_{r=1}^{R} b_{jr} r \log(v_h)^{r-1} + \sum_{k=1}^{K} d_{jk}\vartheta_{hk}\right]\right)\frac{d\log(v_h)}{dz_h},$$

so that the marginal cost of utility for household h is

$$\text{(A6)} \quad P_h^M \equiv \frac{dz_h}{dv_h} = \frac{z_h}{v_h}\left\{1 + \sum_{j=1}^{I}\log(q_{hj})\left[\sum_{r=1}^{R} b_{jr} r \log(v_h)^{r-1} + \sum_{k=1}^{K} d_{jk}\vartheta_{hk}\right]\right\}.$$

Equation (A6) gives the derivative of comprehensive household expenditure with respect to indirect utility, keeping prices constant but allowing for changes in budget shares. This marginal cost of utility equals the average cost of utility (A5) times the term in curly brackets. If all coefficients except the b_{i0}, g_{il} and a_{ij} are zero, demand is homothetic so that $\frac{dz_h}{dv_h} = \frac{z_h}{v_h}$ and $P_h^M = P_h^A$. Generally, demand is not homothetic, in which case the term in curly brackets in (A6) differs from 1 and the marginal cost differs from the average cost of living.