Optimal Environmental Taxation with Capital Mobility*

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Abstract

Climate policy exemptions for energy intensive sectors are often justified with distributional concerns. One concern is that households employed in energy intensive sectors might be affected disproportionally due to (international) capital mobility. By assuming that workers cannot move freely between sectors we can reproduce this concern: uniform climate policy causes more inequality between the sectors when capital is mobile than when it is not. We find, however, that affected households can be relieved more effectively with sector specific labor taxes than with sector-specific climate policy. The reason for this finding is that households benefit more directly from sector-specific labor tax cuts than from climate policy exemptions. Keeping climate policy uniform across sectors has the added benefit of creating incentives for long-term decarbonization. In addition, we find that the differential effect of capital mobility depends on the government's degree of inequality aversion: Redistribution is more expensive when capital is mobile.

JEL classification: H21, H23, Q52

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1 Introduction

How should a government take capital mobility into account when designing environmental policy? There is a strong concern[1] that environmental policy affects energy intensive sectors disproportionally when capital is mobile. This concern motivates environmental policy exemptions for the most affected sectors. Previous research considering sectoral exemptions usually considers one representative household. They find that exemptions are not optimal and conclude that pollution taxes[2] should be uniform across sectors. In this paper we consider sector-specific policy as a means of addressing the sector-specific distributional effects created by the interaction of environmental policy and capital mobility.

We build a model with two sectors of different energy intensity. To reflect the distributional concern we assume sectoral rigidity in labor mobility. The government maximizes a social welfare function which aggregates utility of the households working in the two sectors. The environmental objective is to reduce domestic pollution, motivated for example by the objective to fulfill a carbon reduction target. We then compare the effect of environmental policy with and without capital mobility. We find that indeed environmental policy introduces a bigger difference in utility of the households employed in the two sectors when capital is mobile. Based on this we determine the optimal policy package for reconciling distributional and environmental objectives. We find three major results.

The first result is that sector specific labor taxes are the most suitable instrument to redistribute among the sectors. Sector specific pollution taxes can indeed be justified, but the difference should be very small. In optimum, redistribution between sectors is mainly achieved through relatively large differences in labor taxes. When labor taxes are optimally differentiated between sectors, the difference between utility of the households employed in the different sectors is much smaller than in the scenario where labor taxes are constrained to be uniform.

The second result is that the reaction of the government depends strongly on its inequality aversion. A utilitarian government achieves a higher welfare under capital mobility since it benefits from the gains of (capital) trade. A strongly inequality averse government faces

[1] "A few industrial sectors are energy-intensive and trade-exposed (EITE). Policymakers are often concerned that divergent policy-related costs of energy could lead to the offshoring of economic activity in EITE sectors to jurisdictions with more favourable energy input costs" (?). "Carbon pricing efforts are also increasing, but prices to date are weak, partly due to concerns about damaging industrial competitiveness" (?).

[2] Although climate policy is our lead example, we use the general term "pollution tax", since the analysis applies to environmental policy in general. It also applies to emission trading systems in an equivalent way.

high cost of countering the inequality increasing effect of environmental policy under capital mobility. The cost of redistribution might be so high that it could even be better off without capital mobility.

The third result is that environmental policy creates a greater difference between capital and labor income under capital mobility than in autarky. The government's ability to counter this shift through labor tax cuts is weakened through capital mobility since the reduced demand for pollution means that pollution tax revenues are lower under capital mobility than in autarky.

In addition, we find that the labor tax exemptions in the energy intensive sector can be considered a temporary measure. In the long run workers will adjust to the wage differential. Sectors which are less affected by the pollution tax can pay higher wages. As workers move to these sectors wages will converge and the tax exemptions can be phased out.

The results are based on the idea that energy intensive sectors can be decarbonized. This means that sectors can reduce emissions by substituting them with increased capital investments and/or more labor. This requires that sectors are defined in terms of products like electricity or transportation and not in terms of specific technologies like coal power plants and combustion engine cars. The Intergovernmental Panel on Climate Change (IPCC) and other comprehensive reviews like **?** have established firmly that decarbonization is possible in quite short time frames.

The literature considers two related motivations for pollution tax exemptions, carbon leakage and reduced competitiveness. Neither of these, however, are found to justify differential pollution taxes when other policy instruments are available. Carbon leakage can better be addressed with border tax adjustment (**?**) and reduced competitiveness can be addressed with labor tax reductions (**?**) or generally labor market policy (**?**). We consider a third motivation for sector-specific policy, which is the distributional effects among households employed in different sectors.

Climate policy raises a number of distributional issues, depending on the type of heterogeneity considered, see **?** for an overview. **?** consider households with different types of productivity as in the model of **?**. **?** consider the effect of climate policy on capital and labor income. Related to this is the work of **?** and **?** who consider the effect of climate policy under labor market rigidities. As **?** we model sectoral rigidity in labor mobility, thus considering distributional effects across sectors. While all these models assume capital to be immobile we determine the difference made by capital mobility.

? describe, for both mobile and immobile capital, how environmental taxation can make the tax system more or less efficient depending on the relative taxation of capital and labor. **?** points out that this "strong" double dividend can only occur when the tax system was initially inefficient. We rule out the strong double dividend by letting the government set taxes optimally. A "weak" double dividend of using pollution tax revenues to reduce other distortionary taxes remains of course. The question of efficiency adds an additional aspect: When factors are not freely mobile between sectors, a constraint to tax factors uniformly can constitute an inefficiency. Welfare gains can then be made by allowing differential taxes.

The nature of our analysis requires us to consider two sectors with three production factors each in at least two heterogeneous countries. Given the complexity of the results in the case of three plus two production factors in a closed economy in **?** we consider the setup beyond of what is analytically tractable. We thus solve the model numerically and ensure generality by conducting robustness checks with parameter variations.

Section 2 describes the model and the scenarios with and without capital mobility. Section 3 describes the results in four steps with an increasing number of policy instruments, which allow the government to take distributional effects of environmental policy into account. Section 4 considers the effect of inequality aversion on the relative welfare in autarky and under capital mobility. In Section 5 optimal taxation in the long run, that is with full labor mobility across sectors, is determined. Further results are summarized in Section 6. These include robustness checks, the effect of a capital tax harmonization and leakage. Section 7 concludes.

2 The Model

There are S different countries, each with two sectors of different energy intensity. There is a long-run equilibrium in which all countries maximize "blue" welfare, consisting of consumption of the goods produced in the two sectors, leisure and public good consumption. In this long run equilibrium workers can move between sectors so that there is a unique economy-wide wage. Country 1 then wants to achieve an emission reduction target by maximizing "green welfare" which includes blue welfare plus a term accounting for domestic emissions. In the short run workers cannot move between sectors. The introduction of environmental policy thus introduces sector-specific household utility and wages.

The subindex indicates the country of a variable. K_s^i for example is the amount of capital employed in sector $i \in \{E, N\}$ in country s. The subindex is dropped wherever possible in order to ease notation when no confusion is possible.

Firms. There are two sectors, one of which is energy intensive, E. Firms employ capital K^i, labor L^i and pollution Z^i to produce output $Y^i = f^i(K^i, L^i, Z^i)$. They pay taxes on capital τ^K and sector-specific taxes on labor, τ^{Li}, and pollution, τ^{Zi}. The prices corresponding to the production factors are the interest rate plus tax $r + \tau^K$, the wage plus tax $w^i + \tau^{Li}$ and the pollution tax τ^{Zi}. The profit function of the firm is

$$\Pi^i = p^i f^i(K^i, Z^i, L^i) - (r + \tau^K)K^i - \tau^{Zi} Z^i - (w^i + \tau^{Li})L^i, \quad \forall i \in \{E, N\} \; . \tag{1}$$

The first order conditions of the firm are

$$p^i f_K^i - (r + \tau^K) = 0 \tag{2}$$

$$p^i f_Z^i - \tau^{Zi} = 0 \tag{3}$$

$$p^i f_L^i - (w^i + \tau^{Li}) = 0 \tag{4}$$

Final good producers. Final good producers combine intermediate goods $Y = F(Y^E, Y^N)$. The profit function of the final good producers is

$$\Pi = pF(Y^E, Y^N) - p^E Y^E - p^N Y^N \; . \tag{5}$$

First order conditions thus are

$$pF_{Y^E} - p^E = 0 \tag{6}$$

$$pF_{Y^N} - p^N = 0 \tag{7}$$

Households. The mass of households is normalized to 1 and a mass M^i of households is employed in sector i, so that $M^E + M^N = 1$. How M^i is determined depends on whether the short or long term is considered, see Section 2.3. Household utility depends on individual consumption $\frac{C^i}{M^i}$, individual leisure $\frac{V^i}{M^i}$ and total public good supply G,

$$U^i = U\left(\frac{C^i}{M^i}, \frac{V^i}{M^i}, G\right) \; . \tag{8}$$

The only endogenous choice of the household is the supply of labor. Households thus face the standard labor/leisure trade-off.

Households receive net wages w^i. In addition, all households earn an equal share of capital income from asset holdings A. Household use their income to buy consumption

$$p\frac{C^i}{M^i} = w^i\frac{L^i}{M^i} + rA\ . \tag{9}$$

Since the mass of households has been normalized 1, the individual share in total assets is equal to the total amount of assets, A.

There are M^i workers in sector i. Each has a time budget of 1, so that the total amount of leisure enjoyed in sector i is given by $V^i = M^i - L^i$. The household optimization is

$$\max_{\frac{V^i}{M^i}} U\left(\frac{1}{p}\left(w^i\frac{L^i}{M^i} + rA\right), \frac{V^i}{M^i}, G\right)\ . \tag{10}$$

The optimality condition is thus

$$\frac{w^i}{p}U_{\frac{C^i}{M^i}} = U_{\frac{V^i}{M^i}}\ . \tag{11}$$

In reality, a negative demand shock for labor (induced by environmental policy) can cause unemployment. Voluntary unemployment is included in our model in the form of increasing leisure. However, we use wage reductions as an indicator of lower labor demand instead of involuntary unemployment. Modeling involuntary unemployment would strongly complicate the model without adding much insight: both wage reductions and involuntary unemployment reduce utility of affected households and can be addressed by incentives to increase labor demand.

Government. There are two possible notions of welfare the government may use as its objective function. "Blue" welfare W^b considers a weighted sum of utility from consumption, leisure and public good provision. "Green" welfare W^g considers environmental quality in addition,

$$W^b = \sum_{i\in\{E,N\}} M^i\frac{1}{\rho}\left(U\left(\frac{C^i}{M^i}, \frac{V^i}{M^i}, G\right)\right)^{\rho} \tag{12}$$

$$W^g = \sum_{i\in\{E,N\}} M^i\frac{1}{\rho}\left(U\left(\frac{C^i}{M^i}, \frac{V^i}{M^i}, G\right) - \delta(Z^E + Z^N)^{\varphi}\right)^{\rho}\ . \tag{13}$$

ρ is the degree of inequality aversion. The instruments available to the government are environmental taxes τ^{Zi}, labor taxes τ^{Li} and capital taxes τ^{K}. For technical reasons (otherwise pollution would be infinite) we assume that there is a minimum for the pollution tax, $\tau^{Z} \geq \tau^{Z}_{\min}$. The government purchases the final to provide the public good. The government budget is thus

$$pG = \tau^{K} K + \sum_{i \in \{E,N\}} (\tau^{Li} L^{i} + \tau^{Zi} Z^{i}) . \tag{14}$$

The environmental objective of the government is to reduce *domestic* emissions. See Section 6.3 for a discussion of this policy objective.

Market clearing and numeraire. The amount of pollution used in production is chosen by the firms. The price for pollution is fixed by the government to τ^{Z}.

The total amount of capital used in production is given by the international supply of capital,

$$\sum_{s=1}^{S} A_s = \sum_{s=1}^{S} (K_s^E + K_s^N) . \tag{15}$$

The final good is consumed by the two households and the government for public good production. In addition it can be traded internationally, so that countries effectively exchange capital and the final good.

$$Y - Y^X = C^N + C^E + G . \tag{16}$$

Y^X is the amount of the final good exported. It is positive if the country exports the final good and negative when it imports.

The numeraire good is the final good,

$$p = 1. \tag{17}$$

To close the model, further restrictions are needed. The restrictions depend on the scenario, which will be specified in the next three subsections. One scenario dimension is whether or not capital is mobile internationally. The second scenario dimension is whether the governments objective function is blue or green welfare. The third scenario dimension is whether labor is mobile between sectors or not.

2.1 Capital Mobility

Case 1: Autarky. In case of autarky, total domestic capital is limited by the domestic capital endowment,

$$A_s = K_s^E + K_s^N \quad \forall s \in S \ . \tag{18}$$

Case 2: Capital Mobility. When capital is mobile, borrowed capital must be compensated with the final good Y. The equation for balanced trade thus reads

$$r(K_s^N + K_s^E - A_s) = pY^X \quad \forall s \in S \ . \tag{19}$$

The prices for capital and the final good, r and p, are identical across countries due to the law of one price.

2.2 Environmental Policy

We assume that all governments except in country 1 maximize blue welfare in any case. Country 1 can either maximize blue welfare as well or unilaterally introduce environmental policy by maximizing green welfare.

Case 1: No environmental policy. All governments maximize blue welfare,

$$\max_{\tau_s^{Li},\tau_s^{Zi},\tau_s^K} W_s^b \quad s.t. \quad p_s G_s = \tau_s^K K_s + \sum_{i\in\{E,N\}} (\tau_s^{Li} L_s^i + \tau_s^{Zi} Z_s^i) \quad \forall 1 \le s \le S \ . \tag{20}$$

Case 2: Environmental policy. Government 1 maximizes green welfare while all other governments maximize blue welfare,

$$\max_{\tau_1^{Li},\tau_1^{Zi},\tau_1^K} W_1^g \qquad s.t. \qquad p_1 G_1 = \tau_1^K K_1 + \sum_{i\in\{E,N\}} (\tau_1^{Li} L_1^i + \tau_1^{Zi} Z_1^i), \tag{21}$$

$$\max_{\tau_s^{Li},\tau_s^{Zi},\tau_s^K} W_s^b \qquad s.t. \qquad p_s G_s = \tau_s^K K_s + \sum_{i\in\{E,N\}} (\tau_s^{Li} L_s^i + \tau_s^{Zi} Z_s^i) \quad \forall 2 \le s \le S \ . \tag{22}$$

2.3 Labor mobility

There is a long run equilibrium in which workers allocate freely across sectors. In addition, there is a short run equilibrium in which workers are attached to their sectors. In this case worker shares are fixed to the level they had in the long run equilibrium without environmental policy. This reflects a situation in which a government switches from maximizing blue to maximizing green welfare and workers cannot quickly adapt.

Case 1: Long run equilibrium. The share of workers employed in a sector is equal to the amount of labor employed in this sector,

$$M_s^i = \frac{L_s^i}{L_s^E + L_s^N}, \quad i \in \{E, N\} \ . \tag{23}$$

Case 2: Short run analysis. The allocation of workers is exogenously fixed to the long-run level $M_s^i(LR)$, which corresponds to the worker share obtained in case 1.

$$M_s^i(SR) = M_s^i(LR), \quad i \in \{E, N\} \ . \tag{24}$$

2.4 Functional forms and parameter values

The calibration of the model is based on **?**. They assume factor shares of 25%, 30% and 45% for pollution, capital and labor, respectively, in the energy intensive sector. We also follow this paper on assuming that the N sector accounts for 80% of factor income. Concerning the N sector we assume that the factor share of pollution is 10% and keep a K/L share of roughly 2/3. We also follow **?** by setting the elasticity of substitution for both the factor inputs in the N sector and between the energy intensive and N goods to unity. For the substitution elasticity of factor inputs in the energy intensive sector **?** work with several different values (and they allow the elasticities between the three inputs to be different). We choose an intermediate case of $\sigma_E = 0.4$ and provide a robustness test in Section 6.1. The choice of σ_E reflects the state of research according to which reducing pollution requires additional capital investments, but is feasible (**???**).

Parameter values for all countries are assumed to be identical. In the numerical solution of the model in section 2, we specify the functional forms as follows:

$$f^N(K^N, L^N, Z^N) = \left(0.55(L^N)^{\frac{\sigma_N - 1}{\sigma_N}} + 0.35(K^N)^{\frac{\sigma_N - 1}{\sigma_N}} + 0.1(Z^N)^{\frac{\sigma_N - 1}{\sigma_N}}\right)^{\frac{\sigma_N}{\sigma_N - 1}}, \tag{25}$$

$$f^E(K^E, L^E, Z^E) = \left(0.45(L^E)^{\frac{\sigma_E - 1}{\sigma_E}} + 0.3(K^E)^{\frac{\sigma_E - 1}{\sigma_E}} + 0.25(Z^E)^{\frac{\sigma_E - 1}{\sigma_E}}\right)^{\frac{\sigma_E}{\sigma_E - 1}}, \tag{26}$$

$$F(Y^E, Y^N) = \left((0.2Y^E)^{\frac{\varepsilon - 1}{\varepsilon}} + (0.8Y^N)^{\frac{\varepsilon - 1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon - 1}}, \tag{27}$$

$$U(C^i, V^i, G) = (C^i)^{1-\gamma_1-\gamma_2}(V^i)^{\gamma_1}(G)^{\gamma_2} \ . \tag{28}$$

Parameter values $\sigma_N = 1$ and $\varepsilon = 1$ are taken from **?**. We normalize $A = 1$. The values of $S = 2, \gamma_1 = \gamma_2 = 0.15, \delta = 0.1, \varphi = 2$ and $\tau^Z_{\min} = 0.05$ are set by the authors and have been found to not impact results qualitatively. The values for $\rho = 1$ and $\sigma_E = 0.4$ are set by the authors and subjected to robustness tests in Sections 4 and 6.1.

2.5 The theory of tax incidence

This paper sets out to compare the effectiveness of sectoral pollution tax exemptions to sectoral labor tax exemptions in reducing a concentrated effect of environmental policy on the households in a specific sector. An analytical tax incidence analysis in the style of **?** appears to be a natural approach. Unfortunately, models of taxation and international trade quickly become intractable, so that numerical models came in use early on (**?**). Analytical models remain useful, but are limited to two sector models without trade. More complex models are solved numerically (**?**).

Nevertheless, we can draw a few insights from theoretical analysis. A first insight concerns the importance of the elasticity of substitution between production factors. If pollution and labor are substitutable, the labor tax exemption causes firms to substitute pollution (and capital) with labor. When this margin of adjustment is not available, the difference between the two exemptions (for labor and for pollution) disappears. Consider for example a Leontief production function, $f^E(K^E, L^E, Z^E) = \min(K^E, L^E, Z^E)$. In this case the factor ratios are fixed and only the total cost of production matters. As a consequence there is no difference for any of the outcomes (net wages, pollution, government budget) between a sectoral reduction in labor income taxes or pollution taxes.

A second insight concerns the determinants of tax incidence. The model presented here is an extension of the one in **?**. Extensions include pollution in both sectors (instead of only in one) and capital trade. Equation (11b) in **?** shows the effect of pollution taxes on the wage. It shows that all elasticities (between each pair of inputs in the energy intensive sector sector, between the inputs in the N sector and between the products of the two sectors) affect the transmission from pollution taxes to the wage. The magnitude of the effects of labor and pollution tax cuts is thus determined by all elasticities simultaneously. It is thus not possible to single out "major" determinants of transmission channels.

A third insight can be drawn from considering the effect of pollution and labor taxes on wages, by taking the respective derivatives in equation (4):

$$\frac{dw^i}{d\tau^{Li}} = -1 + \frac{dp^i}{d\tau^{Li}} f_L^i + p^i \left(f_{LK}^i \frac{dK^i}{d\tau^{Li}} + f_{LL}^i \frac{dL^i}{d\tau^{Li}} + f_{LZ}^i \frac{dZ^i}{d\tau^{Li}} \right) , \quad (29)$$

$$\frac{dw^i}{d\tau^{Zi}} = \frac{dp^i}{d\tau^{Zi}} f_L^i + p^i \left(f_{LK}^i \frac{dK^i}{d\tau^{Zi}} + f_{LL}^i \frac{dL^i}{d\tau^{Zi}} + f_{LZ}^i \frac{dZ^i}{d\tau^{Zi}} \right) . \quad (30)$$

A reduction in pollution taxes does affect wages via an increase in the use of pollution. The crucial difference between the effect of the two taxes, however, is the -1 in equation (29), which reflects the direct effect of labor taxes on the wage. This direct effect is the reason why labor tax reductions benefit affected households more directly than pollution tax reductions.

3 Optimal taxes in the short run

We obtain our results by comparing a set of scenarios which are determined by the scenario dimensions discussed in Sections 2.1 to 2.3 as well as the availability of taxes. In this section we present results for the short run case, meaning that whenever we consider environmental policy we assume to be in the case of no labor mobility. Section 3.1 presents the baseline scenarios with uniform labor and pollution taxes and no capital taxes. The following sections allow for progressively more instruments: differential labor taxes, differential pollution taxes and capital taxes. Differential capital taxes are not considered since experiments highlight that the optimizing government makes very little use of this additional possibility when given the choice. Notice that the numbers resulting from the numerical simulation are not meaningful as such. We analyze the relative change between the numbers.

As a general pattern we find that a shift from blue to green welfare causes the government to shift taxation from labor and capital to pollution. This shift provides an incentive to employ more labor and capital and less pollution. Consider for example the electricity producing sector. A tax on pollution (and lower taxes on capital and labor) would make coal power plants less profitable and the production of renewable energy more profitable. Since renewable energy is more capital and labor intensive than fossil fuels (**??**), the entire sector skews production away from pollution and towards capital and labor.

The main results are presented in Tables 1 to 4 in the text. For a more detailed list of results, see the extended Tables 6 to 9 in the Appendix.

3.1 Baseline scenarios with minimal policy instruments

In the baseline scenarios we constrain the government to set uniform pollution and labor taxes across sectors, $\tau^{ZN} = \tau^{ZE}$ and $\tau^{LN} = \tau^{LE}$ and exclude capital taxes, $\tau^{K} = 0$. The objective is to reflect the concern voiced by politicians that environmental policy causes disproportional harm to workers in the energy intensive sector.

Table 1 shows the results for country 1 for the four scenarios in the baseline. In columns 1 and 2 the countries are autarkic, while capital is mobile in columns 3 and 4. In column 1 and 3, country 1 maximizes blue welfare, in columns 2 and 4 it maximizes green welfare. When moving from column 1 to column 2, we see that the change in objective function causes country 1 to introduce a pollution tax above the minimum value. As an immediate consequence, green welfare increases while blue welfare decreases. Since sector E is more pollution intensive and workers cannot move between sectors, utility for workers in sector E is lower than for workers in sector N due to environmental policy. There is almost no difference between columns 1 and 3. The small difference stems from a "race to the bottom" in labor taxes which are used to increase the marginal productivity of capital. The difference is very small, however, since countries are identical and thus all employ the same amount of capital.

The differential effect of capital mobility under environmental policy can thus be analyzed by comparing columns 2 and 4. An immediate effect of capital mobility under environmental policy is that some capital moves abroad and goods are imported in return. Due to the loss of capital, the complementary production factor labor is employed less. The reduced demand for pollution allows the government to achieve its environmental objectives at a lower pollution tax.

On the aggregate, green welfare is higher in the scenario with capital mobility. This aggregate welfare gain is due to the gains of trade effect. There are also distributional effects, however. We compare the green welfare of the respective households, $W^g(i) = U^i - \delta(Z^E + Z^N)$. Households employed in the N-sector benefit from capital mobility and households in the energy-intensive sector experience a small decrease in welfare. This could be seen as a confirmation of the political concern mentioned in the introduction: Under capital mobility, environmental policy introduces a larger difference between households employed in the two sectors than it would in autarky.

Even more dramatic is the effect of capital mobility on factor income. Total labor income

(LI) decreases due to capital mobility and capital income (KI) benefits greatly. The reason is that capital earns the high international interest rate while labor productivity suffers from the loss of the complementary production factor. The interest rate is endogenously determined in the model, but since we consider that only country 1 implements environmental policy, the equalization of marginal productivity of capital requires that the other countries absorb some of the capital owned by country 1.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27019	0.19469	0.27033
W^b	0.31659	0.28610	0.31659	0.28593
$W^g(N)$	0.31659	0.27425	0.31659	0.27453
$W^g(E)$	0.31659	0.25454	0.31659	0.25412
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15084	0.05000	0.14428
τ^{ZE}	0.05000	0.15084	0.05000	0.14428
τ^{LN}	0.04686	0.02825	0.04615	0.03153
τ^{LE}	0.04686	0.02825	0.04615	0.03153

Table 1: Numerical results for the baseline scenarios. See Table 6 for the extended version.

3.2 Differential labor taxes

Starting from the baseline effect we now consider the effect of additional tax instruments in order to equalize the inequality between the workers in the two sectors caused by pollution taxes. As a first redistribution policy we consider differential labor taxes. In order to isolate this effect we continue to impose uniform pollution taxes $\tau^{ZN} = \tau^{ZE}$ and zero capital taxes, $\tau^K = 0$.

Comparison of Tables 1 and 2 shows that sector-specific labor taxes allow the government to make utility $W^g(i)$ across the two sectors more equal. This raises total welfare since utility is concave. The availability of a redistribution instrument makes the introduction of pollution taxes less regressive. The government thus chooses a higher pollution tax and achieves a lower level of total pollution than in the baseline, both in autarky and in capital mobility.

In Table 2 labor taxes are further apart in column 4 than in column 2. Differential labor taxes are thus used to counter the inequality-increasing effect of capital mobility. They allow the government to support the energy intensive sector, which is affected by capital mobility much more than the N-sector. By incentivizing more labor input through lower labor taxes in the energy intensive sector, differential labor taxes also allow retaining more capital in the domestic economy.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15147	0.05000	0.14503
τ^{ZE}	0.05000	0.15147	0.05000	0.14503
τ^{LN}	0.04686	0.03585	0.04615	0.03947
τ^{LE}	0.04686	-0.00241	0.04615	-0.00072

Table 2: Numerical results for differential labor taxes. See Table 7 for the extended version.

3.3 Differential pollution taxes

In addition to sector specific labor taxes we now allow for sector specific pollution taxes as well. This effectively means that the government can give pollution tax exemptions to the individual sectors.

Results in Table 3 show that differential pollution taxes are employed both in autarky and in capital mobility. The additional freedom to design tax policy increases utility for workers in both sectors and consequently aggregate welfare (the difference is too small to reflect in the five digit precision used in the Tables). Distributional effects thus do justify differential pollution taxes.

The differences in optimal pollution taxes, however, are much smaller than in the optimal labor taxes. Labor taxes are thus the better suited instrument of redistribution. While differentiated labor taxes result in a large welfare increase compared to the baseline, the additional welfare increase through differentiated pollution taxes is very small.[3] Distributional concerns thus do not justify large tax exemptions and should rather be seen as a possible tool for detailed refinement of tax policy secondary to differentiated labor taxes.

[3]We also conducted the experiment with differential pollution taxes and uniform labor taxes. The results are very similar to the ones presented here: The optimizing government makes very little use of the possibility to differentiate pollution taxes and achieves hardly any improvement in utility with it.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$	0.31659	0.27174	0.31659	0.27200
$W^g(E)$	0.31659	0.26445	0.31659	0.26414
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15129	0.05000	0.14527
τ^{ZE}	0.05000	0.15207	0.05000	0.14428
τ^{LN}	0.04686	0.03584	0.04615	0.03949
τ^{LE}	0.04686	-0.00267	0.04615	-0.00038

Table 3: Numerical results for differential labor and pollution taxes. See Table 8 for the extended version.

In order to gain an intuitive understanding of *why* differential labor taxes are preferable as a tool for redistribution we conduct an experiment which is shown in Table 11. The first column shows the results of the baseline scenario without climate policy and with uniform pollution, labor and capital taxes (capital is considered not mobile internationally in this experiment). This scenario fixes the shares of workers in the two sectors. The second to fourth columns show the results for policy scenarios in which the government optimizes green welfare.

The second to fourth column each use a different set of policy experiments, that is, differential labor taxes, differential pollution taxes and subsidies for the energy intensive sector. The idea of combining pollution taxes with an output subsidy (implemented in column four) has been shown by **?** to be equivalent to an intensity standard. In each case the government does make use of the respective option to redistribute from the energy intensive to the N sector. The level of green welfare achieved is proportional to the amount of welfare which is shifted from the N sector to the energy intensive sector.

It turns out that the success of the three policy options to achieve a high level of green welfare depends on how directly the workers in the energy intensive sector benefit from the policy. The differential pollution tax is the least direct, since labor benefits only through the channel of more availability of a complementary production factor (pollution). Next is the output subsidy. It benefits all three production factor, so that labor benefits from the sectoral exemption in proportion to the labor share. The differential labor taxes affect the workers directly and thus allow a high degree of redistribution.

3.4 Capital subsidies

In Sections 3.2 and 3.3 we were concerned mainly with redistribution between sectors. A second important aspect, however, is the redistribution effect of environmental policy from labor to capital income. In principle, it would be possible to use capital subsidies to keep capital in the domestic economy. However, these subsidies need to be financed. Higher pollution taxes would counteract the capital subsidies by reducing the marginal productivity of capital. Higher labor taxes would reduce the net return on labor and thus counteract the objective to redistribute from capital to labor income. In this section we thus allow the full set of policies: sector specific labor and pollution taxes as well as capital taxes or subsidies.

Results in Table 4, column 3, show that capital mobility causes a race to the bottom in capital taxes and inefficiently low public good provision as described in **?** and others. The scenario with environmental policy (column 4) shows that an optimizing government does subsidize capital and is able to retain more capital than in the scenario without the capital tax. Due to the capital subsidy labor taxes are increased, but the net effect of capital taxes on labor income is positive (since more domestic capital increases the demand for labor).

The retained capital increases utility for both types of household and is thus a beneficial tool for the government and thus aggregate welfare. On the other hand it increases inequality since almost all of the gains go to the household working in the N sector. Notice that we chose two countries which are identical except in their policy objective. If countries are chosen to be different, in particular with respect to their capital endowment, the scenario with capital mobility will provide higher utility than the scenario of autarky since countries benefit from gains of trade. Our main result here is that a utilitarian government benefits more from capital mobility more than a highly inequality averse government. This continues to hold when non-identical countries are considered.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.18656	0.27041	0.19581	0.27042
W^b	0.31776	0.28633	0.31619	0.28591
$W^g(N)$	0.31776	0.27165	0.31619	0.27209
$W^g(E)$	0.31776	0.26558	0.31619	0.26399
τ^K	0.66476	0.15480	-0.05178	-0.02759
τ^{ZN}	0.05000	0.15335	0.05000	0.14612
τ^{ZE}	0.05000	0.15335	0.05000	0.14612
τ^{LN}	-0.04582	0.00848	0.05886	0.04449
τ^{LE}	-0.04582	-0.03110	0.05886	0.00549

Table 4: Numerical results for the differential labor and pollution taxes and capital taxes. See Table 9 for the extended version.

4 The role of inequality aversion

In equation (13) we defined welfare as an aggregate of utility in the two sectors. The parameter $\rho \leq 1$ indicates the degree of risk aversion by the government. The smaller ρ, the higher the inequality aversion of the government. For $\rho = -\infty$ this yields Rawlsian preferences, for $\rho = 1$ we have unweighted utilitarian preferences. So far, we have worked with the utilitarian case. We use this as our reference, since the concavity of the utility function gives an incentive to redistribute to the government. We now explore the effect of inequality aversion on our results.

In the utilitarian case, aggregate welfare is higher under capital mobility, but while households in the N-sector benefit from capital mobility, households in the E sector have lower welfare, see Table 9, columns 2 and 4. Notice that the welfare gain of capital mobility for an individual household in the N sector is smaller than the welfare loss for an individual household in the E sector. Aggregate welfare increases nevertheless through capital mobility, because there are more households employed in the N sector. Capital mobility thus increases efficiency (by allowing gains of trade) at the expense of higher inequality. This raises the question if capital mobility is an advantage or an obstacle for a government when it is more inequality averse than a utilitarian government.

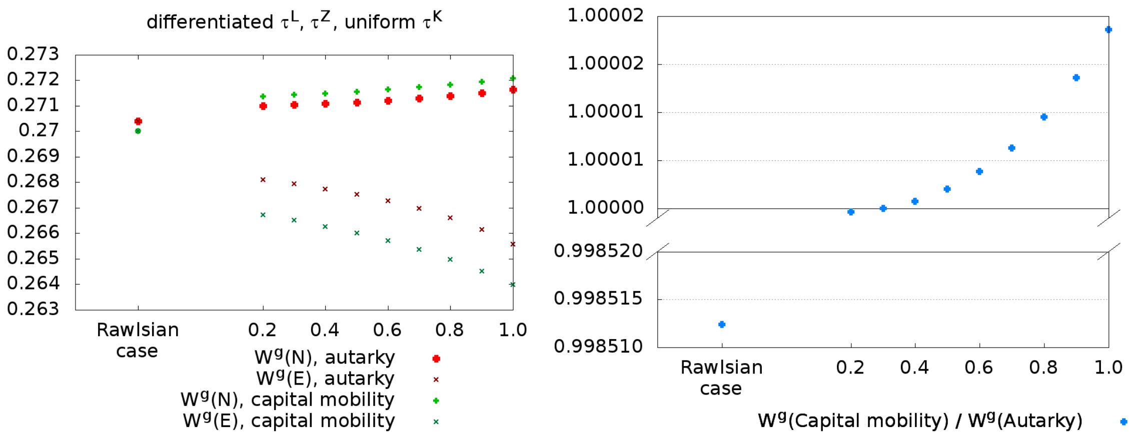

Figure 1: Welfare for different values of inequality aversion

To generate Figure 1 we considered values of ρ of $-\infty, 0.2, 0.3, ..., 1$. The left panel shows the values of $W^g(N)$ and $W^g(E)$ in the scenario with autarky and capital mobility for each value of ρ. The right panel shows the ratio of aggregate welfare of the two scenarios for the different values of ρ. From the left panel we can see that the distribution of utility is always more equal in autarky. In addition, the distribution is more equal for smaller values of ρ. From the right panel we can see that the government would be better off in autarky when it has Rawlsian preferences and in capital mobility when $\rho \geq 0.2$.

Taken together, we can conclude that environmental policy causes higher inequality when capital is mobile. This, however, causes lower aggregate welfare only when the government has an extreme aversion to inequality.

5 Optimal taxes in the long run

In the short run, an energy intensive sector can substitute away from pollution by becoming more capital and labor intensive. In the electricity sector for example, the sector can for example invest in pollution reducing upgrades to existing facilities and shift investments into new capacities from (pollution intensive) fossil fuels towards (capital intensive) renewable energy. In the long run, there are additional margins of adjustment. One of these margins is technological development. In the electricity sector for example it is expected that prices for renewable energy and energy storage will continue falling (?, Section 10.5.2). This process of complete decarbonization through technological development has been analyzed in detail, see **?**.

We thus focus on a second margin, the increased worker mobility across sectors. This becomes relevant when energy intensive sectors reduce total output (and thus employment) as a reaction to the higher cost for pollution. The political justification for sector specific policy was that environmental policy caused a disproportional burden on the energy intensive sector when capital is mobile. We reproduced this skewed effect of environmental policy by assuming sectoral rigidity in the labor market. In this section we show that no sector specific policy is necessary when labor markets adjust freely and we determine the adjustment of optimal policy to capital mobility.

In the long run, households will move from the more energy intensive to the less energy intensive sector. The wage differential between households in the two sectors in column 4 in Table 4, for example, should provide sufficient incentive to do so, in spite of the government subsidies for the energy intensive sector. Table 5 provides the results for the scenario in which the government has all policy options available (as in Section 3.4) and households can move freely between sectors.

Comparing column 4 of Tables 4 and 5 shows that the efficient allocation of labor has the expected effects. A higher share of production factors labor, capital and pollution are used in the N sector in the long run. Production consequently shifts from the E to the N sector as well. The more efficient use of production factors allows the government to attain higher welfare. As households can move into the better paying sector, there is no more need to use sector-specific policy.

Comparing columns 2 and 4 in Table 5 shows how the government optimally adjusts to capital mobility in the long run. The optimal pollution tax is lower under capital mobility since demand for pollution is lower. In addition, labor taxes are increased while capital taxes are decreased, which is an adjustment to capital mobility hardly related to the presence of pollution.

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	Yes	Yes	Yes
W^g	0.18656	0.27064	0.19581	0.27072
W^b	0.31776	0.28628	0.31619	0.28588
$W^g(N)$	0.31776	0.28628	0.31619	0.28588
$W^g(E)$	0.31776	0.28628	0.31619	0.28588
τ^K	0.66476	0.16822	-0.05178	-0.02939
τ^{ZN}	0.05000	0.15221	0.05000	0.14442
τ^{ZE}	0.05000	0.15221	0.05000	0.14442
τ^{LN}	-0.04582	0.00000	0.05886	0.03849
τ^{LE}	-0.04582	0.00000	0.05886	0.03849

Table 5: Numerical results for the long run scenario where households are fully mobile between sectors (shown here are the scenarios where the government can use the full set of policy options: differential labor and pollution taxes and capital taxes). See Table 10 for the extended version.

6 Further Results

6.1 Robustness Checks

We find qualitative results to be robust to changes in parameters. Sector specific policy, however, is necessary only when sectors are affected differently by environmental policy. When the substitution elasticity between production factors is high, the energy intensive sector reacts to higher emission prices by simply substituting emissions with capital. As a consequence, wages across sectors remain similar. The left panel of Figure 2 illustrates this. When the elasticity of substitution increases from $\sigma_E = 0.4$, as it is in the results discussed above, to higher values, the difference between sectors disappears.

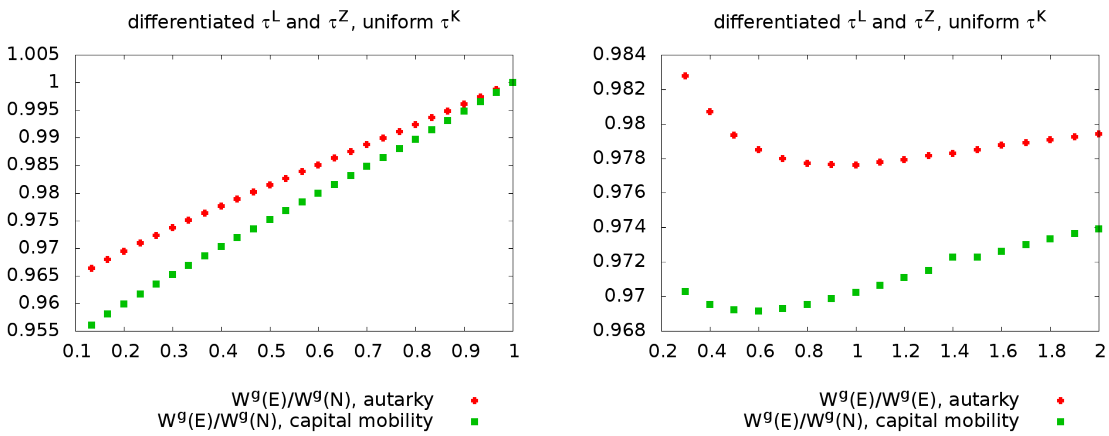

Figure 2: Relative welfare of the sectors for different values of parameters σ_E (left panel) and ε (right panel)

As the right panel of Figure 2 shows, the same does not hold for the substitution elasticity between sectors. The gap between sectors remains at a roughly similar level for a wide range of substitution elasticities.

6.2 Tax Harmonization

? identified a race to the bottom in capital taxes which causes inefficiently low public good provision. This effect can be found in the results in Table 9 by comparing columns 1 and 3. When capital is mobile, capital is subsidized instead of taxed, public good provision is lower and blue welfare is reduced. The effect is less visible in column 4. Aside from the negative effect of tax competition, capital mobility has the positive effect of improving the international allocation of capital whenever countries are not identical. In column 4 countries are not identical because of different policy objectives. Public good provision is thus higher in column 4 than in column 2 since the benefits of capital mobility outweigh the cost.

Comparing Tables 8 and 9 shows what could be achieved by international capital tax harmonization. Results in Table 8 could be seen as the outcome of an international agreement to set capital taxes to zero. Zero is an arbitrary number for the tax harmonization as it is not the socially optimal amount. It serves as a useful experiment nevertheless. For the scenario without environmental policy and with capital mobility (column 3) the scenario with tax harmonization has more public good provision and higher blue welfare. Tax harmonization is thus efficiency enhancing.

When capital is mobile and country 1 pursues environmental policy (column 4), tax harmonization still increases public good provision. Nevertheless, green welfare in country 1 is lower in the scenario with tax harmonization. Higher public good provision increases the demand for output and the lower domestic capital is substituted with pollution to some extent. Both of these effects increase pollution, so that blue welfare increases and green welfare decreases through the tax harmonization.

Interestingly, a capital tax harmonization causes an increase in total pollution when one country is doing environmental policy and the other country is not. The reason is that without the harmonization, the domestic country can reduce capital taxes (or even subsidize capital). This improves the return to capital and increases the amount of capital. Production thus shifts from the country with high emission intensity towards the country which is doing environmental policy and thus has low emission intensity.

6.3 Leakage

Throughout the paper we assumed that country 1 considers only domestic emissions as environmental variable. This is designed to reflect a country's consideration of how much emissions to reduce unilaterally. The aim of such a unilateral policy could be to set a good example. See **?** for possible motivations to implement policy unilaterally.

In spite of this explicit domestic policy focus we can consider the amount of leakage caused by environmental policy as designed in Table 9 for example. Domestic emissions are reduced by 0.704 and foreign emissions increased by 0.048, implying a leakage rate of 6.8%. The leakage rate is thus within the range of 5% to 20% typically identified in the literature (**??**). We consider it suitable that our results are at the lower end of this range, since some models find even negative leakage rates (**??**) and econometric studies find no significant effect at all (**?**). We thus follow the conclusion of **?** that carbon leakage "does not represent a real concern, with a magnitude of at most a few percent of GHG abatement by Annex B countries". The unilateral reduction of domestic pollution without regard for leakage therefore appears to be a legitimate and reasonable policy objective.

However, the risk of carbon leakage is sometimes given as a justification for sectoral climate policy exemptions. We thus compare the amount of leakage which occurs in the case of sectoral pollution tax exemptions with the case of sectoral labor tax exemptions. The increase in pollution abroad depends on the amount of capital which will move abroad as a result of the domestic pollution tax. The reason is that the additional capital allows firms abroad to produce more and thus to demand more pollution. We can thus test directly which policy causes how much additional emission abroad by comparing the amount of capital moving abroad as a result of the different policies. To do this we repeat the experiment in Table 11, this time with international capital mobility.

It turns out that the amount of capital remaining in the domestic economy is almost identical. With pollution tax exemptions total domestic capital is 0.91351, with labor tax exemptions it is 0.91336. The amount of capital moving abroad (and causing leakage) is thus higher in the case of labor tax exemptions, but only by less than 0.2%. We can conclude from this that optimal sectoral exemptions (either in the form of lower labor or of lower pollution taxes) reduce cost for the energy intensive sector in such a way that leakage is contained in a similar degree.

7 Conclusion

This paper considers the differential effect of capital mobility for environmental policy and possible policy reactions. We find that capital mobility can indeed amplify the unequal impact of environmental policy across sectors. The ideal policy instrument to compensate households employed in the energy intensive sector, however, are not sectoral pollution tax exemptions. Sector-specific labor taxes are a much more direct way of relieving their burden, since it benefits them directly and motivates a larger labor input.

Concerning policy implications, this paper thus delivers straightforward results. Environmental policy should be introduced across all sectors with equal stringency. Distributional concerns are a legitimate reason to grant tax reductions to highly affected sectors. These reductions should be applied to labor taxes and not to pollution taxes, because labor tax reductions benefit households more directly. For firms it doesn't make a difference which of their production inputs has lower costs as long as the total reduction is the same.

In the long run, however, the wage differential between the sectors provides an incentive for workers to move away from the energy intensive sector. The sector specific policy should then be phased out. This constitutes another advantage of redistribution through differential labor taxes. Pollution tax exemptions provide no incentive for capital and labor to allocate across sectors in the way it would be optimal in the long run.

A Results

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27019	0.19469	0.27033
W^b	0.31659	0.28610	0.31659	0.28593
$W^g(N)$		0.27425		0.27453
$W^g(E)$		0.25454		0.25412
G	0.08956	0.08090	0.08906	0.07979
Y	0.52006	0.46218	0.52013	0.44117
Y^N	0.68147	0.60840	0.68156	0.57894
Y^E	0.17639	0.15392	0.17642	0.14876
Y^X	0.00000	0.00000	0.00000	-0.01730
C^N	0.43050	0.30971	0.43108	0.30796
C^E	0.43050	0.07157	0.43108	0.07072
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73452	0.73350	0.72300
L^N/L	0.79439	0.79800	0.79440	0.79899
L^E/L	0.20561	0.20200	0.20560	0.20101
$K^N + K^E$	1.00000	1.00000	1.00000	0.89593
K^N	0.82357	0.83641	0.82356	0.74307
K^E	0.17643	0.16359	0.17644	0.15286
Z^N	0.83210	0.24513	0.83221	0.24462
Z^E	0.27184	0.15364	0.27188	0.15040
$L^N w^N + L^E w^E$	0.28805	0.24731	0.28809	0.23524
$(K^N + K^E)r$	0.17681	0.15472	0.17684	0.16624
K^N/L^N	1.41372	1.42697	1.41337	1.28630
K^E/L^E	1.17011	1.10253	1.17000	1.05186
Z^N/L^N	1.42836	0.41821	1.42823	0.42345
Z^E/L^E	1.80290	1.03547	1.80283	1.03490
$w^N + \tau^{LN}$	0.39280	0.34694	0.39276	0.33603
$w^E + \tau^{LE}$	0.39280	0.29622	0.39276	0.28296
r	0.17681	0.15472	0.17684	0.16624
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15084	0.05000	0.14428
τ^{ZE}	0.05000	0.15084	0.05000	0.14428
τ^{LN}	0.04686	0.02825	0.04615	0.03153
τ^{LE}	0.04686	0.02825	0.04615	0.03153
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60773	0.61052	0.60962
p^E	0.58966	0.60053	0.58966	0.59312

Table 6: Numerical results for the baseline scenarios

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$		0.27174		0.27200
$W^g(E)$		0.26445		0.26414
G	0.08956	0.08090	0.08906	0.07981
Y	0.52006	0.46208	0.52013	0.44117
Y^N	0.68147	0.60709	0.68156	0.57756
Y^E	0.17639	0.15508	0.17642	0.15019
Y^X	0.00000	0.00000	0.00000	-0.01722
C^N	0.43050	0.30534	0.43108	0.30350
C^E	0.43050	0.07584	0.43108	0.07508
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73479	0.73350	0.72341
L^N/L	0.79439	0.79564	0.79440	0.79605
L^E/L	0.20561	0.20436	0.20560	0.20395
$K^N + K^E$	1.00000	1.00000	1.00000	0.89648
K^N	0.82357	0.83573	0.82356	0.74276
K^E	0.17643	0.16427	0.17644	0.15371
Z^N	0.83210	0.24404	0.83221	0.24335
Z^E	0.27184	0.15405	0.27188	0.15095
$L^N w^N + L^E w^E$	0.28805	0.24696	0.28809	0.23489
$(K^N + K^E)r$	0.17681	0.15481	0.17684	0.16631
K^N/L^N	1.41372	1.42951	1.41337	1.28980
K^E/L^E	1.17011	1.09398	1.17000	1.04184
Z^N/L^N	1.42836	0.41743	1.42823	0.42257
Z^E/L^E	1.80290	1.02595	1.80283	1.02308
$w^N + \tau^{LN}$	0.39280	0.34777	0.39276	0.33708
$w^E + \tau^{LE}$	0.39280	0.29068	0.39276	0.27638
r	0.17681	0.15481	0.17684	0.16631
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15147	0.05000	0.14503
τ^{ZE}	0.05000	0.15147	0.05000	0.14503
τ^{LN}	0.04686	0.03585	0.04615	0.03947
τ^{LE}	0.04686	-0.00241	0.04615	-0.00072
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60891	0.61052	0.61108
p^E	0.58966	0.59591	0.58966	0.58750

Table 7: Numerical results for differential labor taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.19472	0.27024	0.19469	0.27039
W^b	0.31659	0.28609	0.31659	0.28593
$W^g(N)$		0.27174		0.27200
$W^g(E)$		0.26445		0.26414
G	0.08956	0.08090	0.08906	0.07981
Y	0.52006	0.46208	0.52013	0.44118
Y^N	0.68147	0.60718	0.68156	0.57747
Y^E	0.17639	0.15499	0.17642	0.15030
Y^X	0.00000	0.00000	0.00000	-0.01721
C^N	0.43050	0.30534	0.43108	0.30350
C^E	0.43050	0.07584	0.43108	0.07508
M^N	0.79439	0.79439	0.79440	0.79440
M^E	0.20561	0.20561	0.20560	0.20560
L	0.73333	0.73479	0.73350	0.72341
L^N/L	0.79439	0.79564	0.79440	0.79605
L^E/L	0.20561	0.20436	0.20560	0.20395
$K^N + K^E$	1.00000	1.00000	1.00000	0.89653
K^N	0.82357	0.83578	0.82356	0.74275
K^E	0.17643	0.16422	0.17644	0.15378
Z^N	0.83210	0.24434	0.83221	0.24296
Z^E	0.27184	0.15376	0.27188	0.15133
$L^N w^N + L^E w^E$	0.28805	0.24693	0.28809	0.23494
$(K^N + K^E)r$	0.17681	0.15480	0.17684	0.16631
K^N/L^N	1.41372	1.42958	1.41337	1.28979
K^E/L^E	1.17011	1.09362	1.17000	1.04232
Z^N/L^N	1.42836	0.41793	1.42823	0.42190
Z^E/L^E	1.80290	1.02397	1.80283	1.02570
$w^N + \tau^{LN}$	0.39280	0.34777	0.39276	0.33709
$w^E + \tau^{LE}$	0.39280	0.29043	0.39276	0.27671
r	0.17681	0.15480	0.17684	0.16631
τ^K	0.00000	0.00000	0.00000	0.00000
τ^{ZN}	0.05000	0.15129	0.05000	0.14527
τ^{ZE}	0.05000	0.15207	0.05000	0.14428
τ^{LN}	0.04686	0.03584	0.04615	0.03949
τ^{LE}	0.04686	-0.00267	0.04615	-0.00038
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61052	0.60882	0.61052	0.61119
p^E	0.58966	0.59625	0.58966	0.58706

Table 8: Numerical results for differential labor and pollution taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	No	Yes	No
W^g	0.18656	0.27041	0.19581	0.27042
W^b	0.31776	0.28633	0.31619	0.28591
$W^g(N)$		0.27165		0.27209
$W^g(E)$		0.26558		0.26399
G	0.09520	0.08255	0.08801	0.07961
Y	0.53945	0.46779	0.51690	0.44315
Y^N	0.70655	0.61509	0.67738	0.58052
Y^E	0.18331	0.15649	0.17526	0.15049
Y^X	0.00000	0.00000	0.00000	-0.01458
C^N	0.44425	0.30898	0.42889	0.30308
C^E	0.44425	0.07626	0.42889	0.07504
M^N	0.79669	0.79669	0.79401	0.79401
M^E	0.20331	0.20331	0.20599	0.20599
L	0.77798	0.75128	0.72615	0.72132
L^N/L	0.79669	0.79744	0.79401	0.79577
L^E/L	0.20331	0.20256	0.20599	0.20423
$K^N + K^E$	1.00000	1.00000	1.00000	0.91336
K^N	0.81979	0.83490	0.82420	0.75819
K^E	0.18021	0.16510	0.17580	0.15517
Z^N	0.86312	0.24403	0.82703	0.24262
Z^E	0.28228	0.15489	0.27013	0.15094
$L^N w^N + L^E w^E$	0.29793	0.24973	0.28644	0.23617
$(K^N + K^E)r$	0.11068	0.13585	0.18519	0.16830
K^N/L^N	1.32265	1.39359	1.42948	1.32087
K^E/L^E	1.13936	1.08490	1.17531	1.05333
Z^N/L^N	1.39256	0.40734	1.43440	0.42267
Z^E/L^E	1.78468	1.01782	1.80594	1.02466
$w^N + \tau^{LN}$	0.38295	0.34356	0.39446	0.33969
$w^E + \tau^{LE}$	0.38295	0.28850	0.39446	0.27954
r	0.11068	0.13585	0.18519	0.16830
τ^K	0.66476	0.15480	-0.05178	-0.02759
τ^{ZN}	0.05000	0.15335	0.05000	0.14612
τ^{ZE}	0.05000	0.15335	0.05000	0.14612
τ^{LN}	-0.04582	0.00848	0.05886	0.04449
τ^{LE}	-0.04582	-0.03110	0.05886	0.00549
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61080	0.60842	0.61046	0.61070
p^E	0.58858	0.59784	0.58987	0.58896

Table 9: Numerical results for the differential labor and pollution taxes and capital taxes

Capital mobile?	No	No	Yes	Yes
Welfare	Blue	Green	Blue	Green
Households mobile?	Yes	Yes	Yes	Yes
W^g	0.18656	0.27064	0.19581	0.27072
W^b	0.31776	0.28628	0.31619	0.28588
$W^g(N)$		0.28628		0.28588
$W^g(E)$		0.28628		0.28588
G	0.09520	0.08264	0.08801	0.07953
Y	0.53945	0.46831	0.51690	0.44190
Y^N	0.70655	0.62636	0.67738	0.58984
Y^E	0.18331	0.14635	0.17526	0.13922
Y^X	0.00000	0.00000	0.00000	-0.01582
C^N	0.44425	0.38567	0.42889	0.37819
C^E	0.44425	0.38567	0.42889	0.37819
M^N	0.79669	0.81706	0.79401	0.81777
M^E	0.20331	0.18294	0.20599	0.18223
L	0.77798	0.75318	0.72615	0.72154
L^N/L	0.79669	0.81706	0.79401	0.81777
L^E/L	0.20331	0.18294	0.20599	0.18223
$K^N + K^E$	1.00000	1.00000	1.00000	0.90597
K^N	0.81979	0.84095	0.82420	0.75790
K^E	0.18021	0.15905	0.17580	0.14807
Z^N	0.86312	0.24614	0.82703	0.24479
Z^E	0.28228	0.14930	0.27013	0.14457
$L^N w^N + L^E w^E$	0.29793	0.25219	0.28644	0.23777
$(K^N + K^E)r$	0.11068	0.13348	0.18519	0.16820
K^N/L^N	1.32265	1.36652	1.42948	1.28446
K^E/L^E	1.13936	1.15432	1.17531	1.12608
Z^N/L^N	1.39256	0.39997	1.43440	0.41487
Z^E/L^E	1.78468	1.08355	1.80594	1.09951
$w^N + \tau^{LN}$	0.38295	0.33484	0.39446	0.32952
$w^E + \tau^{LE}$	0.38295	0.33484	0.39446	0.32952
r	0.11068	0.13348	0.18519	0.16820
τ^K	0.66476	0.16822	-0.05178	-0.02939
τ^{ZN}	0.05000	0.15221	0.05000	0.14442
τ^{ZE}	0.05000	0.15221	0.05000	0.14442
τ^{LN}	-0.04582	0.00000	0.05886	0.03849
τ^{LE}	-0.04582	0.00000	0.05886	0.03849
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61080	0.59814	0.61046	0.59935
p^E	0.58858	0.63999	0.58987	0.63484

Table 10: Numerical results for the long run scenario where households are fully mobile between sectors (shown here are the scenarios where the government can use the full set of policy options: differential labor and pollution taxes and capital taxes)

Capital mobile?	no	no	no	no
Welfare	blue	green	green	green
Households mobile?	yes	no	no	no
capital taxes	uniform	uniform	uniform	uniform
labor taxes	uniform	differentiated	uniform	uniform
pollution taxes	uniform	uniform	differentiated	uniform
output subsidy	not available	not available	not available	only in E-Sektor
W^g	0.18656	0.27041	0.27037	0.27039
W^b	0.31776	0.28633	0.28634	0.28634
$W^g(N)$		0.27165	0.27429	0.27318
$W^g(E)$		0.26558	0.25501	0.25945
G	0.09520	0.08255	0.08251	0.08252
Y	0.53945	0.46779	0.46774	0.46772
Y^N	0.70655	0.61509	0.61555	0.61390
Y^E	0.18331	0.15649	0.15594	0.15759
Y^X	0.00000	0.00000	0.00000	0.00000
C^N	0.44425	0.30898	0.31345	0.31155
C^E	0.44425	0.07626	0.07178	0.07365
M^N	0.79669	0.79669	0.79669	0.79669
M^E	0.20331	0.20331	0.20331	0.20331
L	0.77798	0.75128	0.75063	0.75084
L^N/L	0.79669	0.79744	0.79924	0.79846
L^E/L	0.20331	0.20256	0.20076	0.20154
$K^N + K^E$	1.00000	1.00000	1.00000	1.00000
K^N	0.81979	0.83490	0.83523	0.83165
K^E	0.18021	0.16510	0.16477	0.16835
Z^N	0.86312	0.24403	0.24366	0.24173
Z^E	0.28228	0.15489	0.15588	0.15758
$w^N + \tau^{LN}$	0.38295	0.34356	0.34305	0.34328
$w^E + \tau^{LE}$	0.38295	0.28850	0.29405	0.30832
r	0.11068	0.13585	0.13638	0.13628
τ^K	0.66476	0.15480	0.14977	0.15554
τ^{ZN}	0.05000	0.15335	0.15357	0.15479
τ^{ZE}	0.05000	0.15335	0.15011	0.15479
τ^{LN}	-0.04582	0.00848	0.00168	0.00471
τ^{LE}	-0.04582	-0.03110	0.00168	0.00471
subsidy Y^N	0.00000	0.00000	0.00000	0.00000
subsidy Y^E	0.00000	0.00000	0.00000	0.04292
p	1.00000	1.00000	1.00000	1.00000
p^N	0.61080	0.60842	0.60789	0.60951
p^E	0.58858	0.59784	0.59991	0.59358

Table 11: Comparison of three policy option for reducing the burden for households employed in the E sector without international capital mobility. See Section 3.3 for a discussion.

B Game theory approach and numerical solution

We frame the optimization problem as a non-linear program and solve the economy for the Nash equilibrium using the GAMS software (**?**). Thus, all economic agents (households and firms) take the strategies of the other agents as given. The governments of the countries have an advantage, though, as they are assumed to be Stackelberg leaders and may move first, or, to formulate it in different terms, they anticipate the reactions of firms and households.

At the same time, one country's government also faces the other countries' governments, Stackelberg leaders of the global economy as well. Thus, governments sit at two game tables – here a Stackelberg and there a simultaneous move game. In the former sub-game, governments have to make decisions about financing the local public good and redistributing income. They have to trade off the advantages of regulating the economy with the distortions caused by the use of regulation. In the latter, all governments can interact strategically with each other through the choice of policy instruments.

Each government takes the strategies of the other governments as given when choosing its own strategy. In doing so, it anticipates the international movement of capital, but also the behavior of domestic and foreign households and firms in response to the policy instrument choice.

To find a Nash equilibrium, we apply the algorithm developed by **?**:

```
until policy instruments converge
    repeat for each player j:
        unfix policy variables
        optimize player j's payoff/welfare
        fix player j's newly found policy variables
```