

# Climate Policies and Structural Change - Employment and Output Effects of Sustainable Growth

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Working Paper

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## Abstract

*Recently academic work has been put forward that argues for a great urgency to implement effective climate policies to stop global warming. Concrete policy proposals for reducing CO<sub>2</sub> emissions have been developed by the IPCC. This paper considers, in the context of a growth model with structural change, three types of policies: 1) changing households' preferences, 2) imposing carbon tax and subsidizing labor (or reducing overhead cost for labor), and 3) imposing carbon tax and subsidizing the development of less carbon intensive products. In the empirical part of the paper the effects of those policy measures on structural change of output and employment are explored. In order to do so the carbon intensities of industries for the German economy is computed, the industries are ranked in terms of carbon intensity and the empirical effects of the above three policy measures evaluated. The evaluation of the policies is undertaken by the use of a new type of a VAR method that allows for budgetary neutrality. The empirical results show that in particular the third policy measure allows for net gains in terms of output and employment.*

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# 1 Introduction

Given the recently published scientific evidence on global warming and its damages, as documented in the numerous reports by the IPCC, the importance of climate mitigation has been sufficiently demonstrated. The need for climate actions becomes particularly urgent if the positive feedback effect of “temperature on temperature” through the endogenous albedo effect holds true.<sup>1</sup> This produces the danger of doing “too little too late.” In Greiner and Semmler (2008) and Greiner, Gruene, and Semmler (2009), models are presented that motivate a great urgency. As shown there, discount rates which have heavily been stressed in previous academic studies (see Nordhaus (2008), Weitzmann (2008) and Stern (2007)) are not as important as the danger of delaying actions. Delaying action can mean that a high temperature (and low growth path) is approached that becomes irreversible.

Correspondingly, the last report by the IPCC (2007) (4th Assessment Report) has urgently suggested a broad range of mitigation policy measures, such as integrating climate policies, broader development policies, regulations and standards, voluntary agreements, information instruments and financial incentives to control and reduce Greenhouse Gas (GHG) emission.

It also emphasizes the role of technology policies to achieve lower  $CO_2$  stabilization levels, a greater need for more efficient R&D efforts, and higher investment in new technologies during the next few decades (for achieving stabilization and reducing costs). Further recommendations include government initiatives for funding or subsidizing alternative energy sources (solar energy, ocean power, windmills, biomass, and nuclear fusion). Overall, the IPCC stresses the fact that the effectiveness of such policies ultimately depends on national circumstances, their design, interaction, stringency and implementation.

Yet, the major instruments that the IPCC and numerous well-respected economists propose are two specific tools to reduce GHG in order to fulfill the agreements of the Kyoto protocol. These two tools are decentralized market trading of emission right and carbon taxation – in the public discussion often called “cap-and trade” and “carbon tax” (see Uzawa (2003) , Nordhaus (2008), Mankiw (2007) and also the IPCC (2007)). Both measures have a long standing history in economic theory originating in the works of Pigou and Coase. Indeed, most economists seem to agree that an emission (or carbon) tax is preferable to a cap-and-trade system (see e.g. Nell, Semmler, and Rezai (2009) for a discussion about advantages and disadvantages of the two systems). We here focus on tax schemes as regulatory instrument.

Our subsequently proposed model is also a growth model, but in contrast to much recent work it allows for structural change due to policy influences. In economics models that allow to study simultaneously growth and structural change have been developed by Kuznets (1957), Kaldor (1968) and Pasinetti (1981) in the context of traditional Keynesian oriented growth models. In Pasinetti (1981), for example, structural change occurs through a change in final demand — driven by the income elasticity of demand (Engel curves). The Kuznets-Kaldor-Pasinetti ideas are incorporated into a recent optimal growth model that allows for structural change, see Kongsamut, Xie and

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<sup>1</sup>The albedo effect refers to the reflection of incoming energy from the sun. As scientists have found out, the amount of energy reflected back to space is decreasing as the earth becomes warmer. The melting of the arctic ice, for example, leads to an absorption of a higher fraction of energy by the earth and the amount of energy reflected back to space, the albedo, falls. This in turn heats up the earth faster, see Lovelock (2007).

Rebelo (2001). In the latter work, three types of preferences are driving structural change: Preferences for agricultural goods, manufactured goods and services. The authors call such a model a generalized balanced growth model, since it has the feature that there is a reallocation of labor and capital at the growth path. Since those models allow for structural change along the growth path we use them as starting point to model the impact of climate policies on structural change and employment.

Although the ICCP has suggested a variety of policy measures, it has not employed a dynamic economic model to study the effects of those policy measures in detail. In most existing approaches, production activities are targeted to reduce  $CO_2$ . Our major approach here is to consider the way those policy measures may work through preferences, production activities and industry and employment structures.

One can generally distinguish different factors that have an effect on total  $CO_2$  emissions of an economy (Proops, Faber, and Wagenhals, 1993):<sup>2</sup> the  $CO_2$  intensity of the energy sources used:  $\frac{C}{E}$ ; the energy intensity of the production:  $\frac{E}{TO}$ ; total output,  $TO$ . total output effects can be further decomposed into the structure of intermediate goods, the structure of final demand and the volume of final demand. Thus, all climate policies have to influence ultimately at least one of the previous five factors. It is important to note that  $TO$  can affect  $CO_2$  emissions through its level *and* through its structure.

Furthermore, we can distinguish one portion of total output that directly satisfies final demand and another portion that is used to produce intermediate goods. However, the volume of intermediate goods produced will directly depend on the volume of final goods demanded. (We will later propose a type of carbon tax which emphasizes a dependency of the structure of intermediate goods on the structure of final demand). For lasting and long-term results, climate policies should initiate and promote a structural change of the economy and this cannot be achieved without a change of the demand structure.

Regarding this connection, we here are considering mainly three ways of how carbon intensity of an economy might be reduced:

- Preferences can shift over time, away from carbon intensive and towards less carbon intensive industries. This implies that the final demand will change
- Carbon intensive sector entering final demand can be taxed and the tax revenue can be used to reduce wage cost. This is often seen a policy measure that generates a double dividend.
- Carbon intensive sectors and products can be taxed and less carbon intensive sectors and products can be subsidized.

Yet, one also needs to affect the capital goods sector and its generation of  $CO_2$ . We will show

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<sup>2</sup>This can be seen from the following identity:

$$C \equiv \frac{C}{E} \cdot \frac{E}{TO} \cdot TO$$

with  $C$  denoting absolute  $CO_2$  emissions,  $E$  energy use, and  $TO$  standing for the total output of the economy. We can therefore identify the five listed factors that affect  $CO_2$  emissions.

that also the carbon intensity of the capital goods sector that delivers inputs to the final goods sector can be reduced which will finally reduce the carbon intensity of the economy. Thus although we are considering a capital goods sector our model makes preferences for final goods central. What we are claiming is that preferences shape the final demand of goods, and hence the  $CO_2$  emissions of the economy. If preferences are redirected from high to low carbon intensity goods, overall carbon intensity will be reduced. If for an industry, preferences are redirected to products with less carbon intensity, an industry's carbon intensity will also be reduced. As we will show later this implies a change of final demand which will entail a change of the carbon intensity of the capital goods sector as mentioned above. We will show that even if the capital goods sector is not given direct incentive to reduce carbon intensity, a reduction will indirectly occur through changed preferences of the final goods.<sup>3</sup>

As to the first point, however, the question is how to impact preferences through policies in such a way that they change in the right direction. Preferences are often evolving historically and are impacted by sociological and cultural factors, for example through role models and adapting the behavior or others. Conspicuous consumption in the sense of Veblen is another example which leads to a certain preference adoption. Population segments may copy the behavior of other population segments as Veblen suggested.

Preferences may also be given incentives to change through regulations and standards, norms and conventions. development policies, voluntary agreements and information instruments. If standards and rules are set for construction of housing. and for fuel efficiency of cars then preferences are likely to change over time. Moral persuasion is another way to change preferences.

Moreover – and this concerns the above second and third point— there are more direct policy tools to change preferences and final demand. Preferences may be changed through financial incentives, such as taxes, emission certificates and subsidies. These policy tools are likely to affect strongly individual behavior of buying goods and this can help to redirect preferences to less carbon incentive sectors and goods.

In our subsequent model, we first will consider indirect influences on preferences by looking at the way how private preferences are shaped over time. This will represent our baseline model which is presented in section 3. In the second version of our model, in section 4, we study the issue when a carbon tax (or tradable emission permits) are imposed and the revenue is used to reduce tax rate on labor or subsidies labor cost.<sup>4</sup> In a third version of our model, in section 5, we consider a further extension where we allow for both carbon taxes on emission intensive products and subsidization of low carbon intensive products. The latter model will exhibit what has been called a generalized steady state. Although there are some common growth rates there will be a structural change and thus a change of the composition of sectors over time. Thus, the output composition of the economy and the fraction of labor and capital employed will change over time.

Although in all of our versions we will study the effects of an active environmental policy on

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<sup>3</sup>Note: One could also introduce a financial penalty, for example a tax on the use of capital goods or intermediate goods with high direct and indirect carbon emission. A VAT on consumption whose rates are based on the cumulated carbon intensity could achieve this.

<sup>4</sup>This was a policy introduced by the German Government in 1998, yet in the subsequent period there were exemptions made for certain heavy industries.

preferences output and employment, an empirical study will be added in section 6 of the paper, where a VAR is used to study the impact of a neutral shift— neutral in a budgetary sense— of labor from high to low emission intensive products. Here a data set from Germany is used, but we consider it as prototypical for other advanced countries as well.

## 2 A Baseline Model with Preferences

The baseline model (see Kongsamut, Rebelo, and Xie, 2001) sets up the basic mechanism of how our model works. We also show here what role preferences play for the sectoral composition of the economy and how preferences can evolve over time.

### Allocation of labor and capital

There are two factors of production, capital  $K_t$  and labor  $L$  ( $=1$ , normalized), available in the economy. Denote the fraction of capital devoted to sector  $i$  as  $\phi_t^i K_t$  where

$$\sum \phi_t^i = 1, \quad (1)$$

and the fraction of labor devoted to sector  $i$  as  $N_t^i$  where

$$\sum N_t^i = 1, \quad (2)$$

for  $i = H$  (High- $CO_2$ -emitting sector),  $L$  (Low- $CO_2$ -emitting sector), and  $K$  (capital-goods sector).

### Technology and production

Three sectors (high- $CO_2$ -emitting sector, capital-goods sector, and low- $CO_2$ -emitting sector) have identical production functions  $F$  with constant returns to scale. The level of technological progress is denoted by  $X_t$  and the path of  $X_t$  is given. We, however, assume that the growth rate of technology gradually converges to a constant rate  $g$ .

$$\lim_{t \rightarrow \infty} g_t = g \geq 0. \quad (3)$$

Assume that it is labour augmenting.

$$\dot{X}_t = X_t g_t \quad (4)$$

Output of the high- $CO_2$ -emitting sector is

$$H_t = B_H F(\phi_t^H K_t, N_t^H X_t). \quad (5)$$

Output of the low- $CO_2$ -emitting sector is

$$L_t = B_L F(\phi_t^L K_t, N_t^L X_t). \quad (6)$$

Output of the capital-goods sector can be only invested  $\dot{K}_t + \delta K_t$

$$\dot{K}_t + \delta K_t = B_K F(\phi_t^K K_t, N_t^K X_t). \quad (7)$$

## Efficient allocation

As three sectors have identical  $F$ , efficiency of production in each sector should be measured by  $B_i$  only. Then, the fraction of capital and the fraction of labor used in sector  $i$  should be the same. An efficient allocation requires that the marginal rate of transformation be equated across the three production sectors

$$\frac{\phi_t^H}{N_t^H} = \frac{\phi_t^K}{N_t^K} = \frac{\phi_t^L}{N_t^L} = 1. \quad (8)$$

Again, the price  $P_i$  should reflect efficiency of production in sector  $i$ . The higher the efficiency is, the lower the price is. Then, the relative prices of high- $CO_2$ -emitting products and low- $CO_2$ -emitting products in terms of capital goods are

$$P_H = \frac{B_K}{B_H} \text{ and } P_L = \frac{B_K}{B_L} \text{ when } P_K = 1. \quad (9)$$

## Budget constraint

From Eqs. (5), (8), and (9), total revenue from high- $CO_2$ -emitting products is

$$\begin{aligned} P_H H_t &= P_H B_H N_t^H F(K_t, X_t) \\ &= B_K N_t^H F(K_t, X_t), \end{aligned} \quad (10)$$

and from Eqs. (6), (8), and (9), total revenue from low- $CO_2$ -emitting products is

$$\begin{aligned} P_L L_t &= P_L B_L N_t^L F(K_t, X_t) \\ &= B_K N_t^L F(K_t, X_t). \end{aligned} \quad (11)$$

Then, from Eqs. (2), (7), (8), (10), and (11),

$$\begin{aligned} \dot{K}_t + \delta K_t &= B_K N_t^K F(K_t, X_t) \\ &= B_K (1 - N_t^H - N_t^L) F(K_t, X_t) \\ &= B_K F(K_t, X_t) - P_H H_t - P_L L_t. \end{aligned} \quad (12)$$

## Preference

Assume a CRRA (Constant Relative Risk Aversion) type utility function

$$U_t = \int_0^\infty e^{-\rho t} \frac{[H_t^\beta L_t^\theta]^{1-\sigma} - 1}{1-\sigma} dt \quad (13)$$

where parameters  $\rho$ ,  $\beta$ ,  $\theta$ ,  $\sigma$  are all strictly positive.

## Competitive equilibrium

At equilibrium marginal products of capital = marginal costs of capital.

From Eq. (7), production in capital-goods sector is

$$B_K F(\phi_t^K K_t, N_t^K X_t) = B_K N_t^K X_t F(k_t, 1), \quad (14)$$

where  $k_t \equiv \phi_t^K K_t / N_t^K X_t = K_t / X_t$ .

Cost of capital is

$$(r + \delta) \phi_t^K K_t = (r + \delta) N_t^K X_t k_t. \quad (15)$$

Thus at equilibrium,

$$\begin{aligned} (r + \delta) N_t^K X_t &= B_K N_t^K X_t F_1(k_t, 1) \\ r + \delta &= B_K F_1(k_t, 1). \end{aligned} \quad (16)$$

## Optimal consumption

Let's first define output per unit of efficiency labor as

$$h_t \equiv \frac{H_t}{X_t}, \quad l_t \equiv \frac{L_t}{X_t}.$$

Dividing both sides of Eq. (12) by  $X_t$  gives

$$\frac{\dot{K}_t}{X_t} + \delta k_t + P_H h_t + P_L l_t = B_K F(k_t, 1). \quad (17)$$

where  $k_t \equiv K_t / X_t$ , capital per unit of efficiency labor.

Inserting the fact

$$\dot{k}_t = \frac{\dot{K}_t}{X_t} - g k_t$$

into Eq. (17) gives the per-efficiency labor budget constraint

$$\dot{k}_t + (g_t + \delta) k_t + P_H h_t + P_L l_t = B_K F(k_t, 1). \quad (18)$$

Rewriting the utility function Eq.(13) using per-efficiency-labor variables,

$$U_t = \int_0^\infty e^{-\rho t} \frac{[(h_t X_t)^\beta (l_t X_t)^\theta]^{1-\sigma} - 1}{1-\sigma} dt \quad (19)$$

where  $\beta + \theta = 1$ .

To get an optimal solution to

$$\max_{h_t, l_t} \text{Eq. (19)}$$

subject to Eq. (18), for given  $k_0 > 0$ , we set the Hamiltonian as

$$\Phi_t \equiv \frac{\left[ (h_t X_t)^\beta (l_t X_t)^\theta \right]^{1-\sigma} - 1}{1-\sigma} + q_t [B_K F(k_t, 1) - P_H h_t - P_L l_t - (\delta + g_t) k_t]. \quad (20)$$

The first-order necessary conditions are

$$[\cdot]^{-\sigma} \beta (h_t X_t)^{\beta-1} (l_t X_t)^\theta X_t = P_H q_t, \quad (21)$$

and

$$[\cdot]^{-\sigma} \theta (h_t X_t)^\beta (l_t X_t)^{\theta-1} X_t = P_L q_t. \quad (22)$$

The law of motion of the costate  $q_t$  is

$$\dot{q}_t = \rho q_t - [B_K F_1(k_t, 1) - (\delta + g_t)] q_t. \quad (23)$$

From Eqs. (21) and (22),

$$\frac{\beta}{\theta} \left( \frac{l_t}{h_t} \right) = \frac{P_H}{P_L}. \quad (24)$$

Thus, in equilibrium,

$$\frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} = \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t} \equiv \kappa \quad (25)$$

By taking a time-derivative of the natural log of Eq. (21), and we get

$$-\sigma \left\{ \beta \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} \right\} + (\beta - 1) \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} + \frac{\dot{X}_t}{X_t} = \frac{\dot{q}_t}{q_t},$$

but from Eq. (25) and  $\beta + \theta = 1$ ,

$$\kappa = -\frac{1}{\sigma} \left( \frac{\dot{q}_t}{q_t} - g_t \right). \quad (26)$$

From Eqs. (16) and (23), the law of motion of  $q_t$  is

$$\frac{\dot{q}_t}{q_t} = \rho - r + g_t. \quad (27)$$

Thus, from Eqs. (26) and (27),

$$\kappa = \frac{r - \rho}{\sigma}. \quad (28)$$

## Balanced growth

The growth rate of technology  $g_t$ , by assumption, approaches a constant rate  $g$ . Thus in balanced growth, Eq. (25) becomes

$$\frac{\dot{l}_t}{l_t} = \frac{\dot{h}_t}{h_t} = \kappa - g.$$

From Eq. (18), the growth rate of  $k_t$  is

$$\dot{k}_t = B_K F(k_t, 1) - P_H h_t - P_L l_t - (g + \delta) k_t.$$

For  $k_t$  to be constant,  $h_t$  and  $l_t$  must be also constant, i.e.,

$$\kappa - g = 0. \quad (29)$$

Denote the steady state values by  $k^*$ ,  $h^*$ , and  $l^*$ . Then,

$$B_{KF}(k^*, 1) = (g + \delta)k^* + P_H h^* + P_L l^*. \quad (30)$$

From Eq. (24),

$$P_L l^* = \frac{\theta}{\beta} P_H h^* \quad (31)$$

Inserting Eq. (31) into Eq. (30) gives

$$B_{KF}(k^*, 1) = (g + \delta)k^* + \frac{1}{\beta} P_H h^*. \quad (32)$$

From Eqs. (28) and (29), the equilibrium interest rate  $r$  is

$$r = \rho + \sigma g. \quad (33)$$

Then, from Eqs. (16) and (33), the steady state value  $k^*$  should satisfy

$$\rho + \sigma g + \delta = B_{MF_1}(k^*, 1). \quad (34)$$

From Eq. (32), the steady state value  $h^*$  is

$$h^* = \frac{\beta}{P_H} [B_{KF}(k^*, 1) - (g + \delta)k^*], \quad (35)$$

and from Eq. (31), the steady state value  $l^*$  is

$$l^* = \frac{\theta}{P_L} [B_{KF}(k^*, 1) - (g + \delta)k^*]. \quad (36)$$

## Output and employment

In balanced growth, the output in high- $CO_2$ -emitting sector and the output in low- $CO_2$ -emitting sector grow at the technological growth rate  $g$ , i.e.,

$$H_t^* = \frac{\beta}{P_H} [B_{KF}(k^*, 1) - (g + \delta)k^*] X_t, \quad (37)$$

and

$$L_t^* = \frac{\theta}{P_L} [B_{KF}(k^*, 1) - (g + \delta)k^*] X_t. \quad (38)$$

From Eqs. (5) and (35), employment of the high- $CO_2$ -emitting sector

$$N^{H^*} = \frac{\beta}{P_H B_{HF}(k^*, 1)} [B_{KF}(k^*, 1) - (g + \delta)k^*], \quad (39)$$

and similarly, from Eqs. (6) and (36), employment of the low- $CO_2$ -emitting sector is

$$N^{L^*} = \frac{\theta}{P_L B_{LF}(k^*, 1)} [B_{KF}(k^*, 1) - (g + \delta)k^*]. \quad (40)$$

Finally, from Eqs. (2), (39), and (40), employment of the capital-goods sector is

$$N^{K^*} = 1 - N^{H^*} - N^{L^*}. \quad (41)$$

### 3 Preferences, Carbon Tax and Wage Subsidies

#### A Carbon Tax

For such a version of a dynamic decision model with preferences we could rewrite the above model with the utility function of Eq.(13), but including a tax on high carbon emission sectors, in our model aggregated as  $h_t X_t$ . Note that for  $X_t$  as a constant we would have  $h_t X_t = H_t$  :

$$U_t = \int_0^\infty e^{-\rho t} \frac{\left[ (h_t X_t - \bar{H})^\beta (l_t X_t)^\theta \right]^{1-\sigma} - 1}{1-\sigma} dt \quad (42)$$

with  $\beta + \theta = 1$ .

In this version we suggest to introduced a tax  $\bar{H}$  which is imposed on a consumption goods with high carbon intensity.

#### Consumption under carbon tax

For reasons of simplicity we take an absolute tax  $\bar{H}$ .

In order to get an optimal solution to

$$\max_{h_t, l_t} \text{Eq. (42)}$$

subject to Eq. (18), for given  $k_0 > 0$ , we set the Hamiltonian as

$$\Psi_t \equiv \frac{\left[ (h_t X_t - \bar{H})^\beta (l_t X_t)^\theta \right]^{1-\sigma} - 1}{1-\sigma} + q_t [B_K F(k_t, 1) - P_H h_t - P_L l_t - (\delta + g_t) k_t]. \quad (43)$$

We assume here that the tax  $\bar{H}$  is part of the product price that the consumer has to pay.

This has the effect that the demand for this high carbon intensive industries will decline.

The new first-order necessary conditions are

$$[\cdot]^{-\sigma} \beta (h_t X_t - \bar{H})^{\beta-1} (l_t X_t)^\theta X_t = P_H q_t, \quad (44a)$$

and

$$[\cdot]^{-\sigma} \theta (h_t X_t - \bar{H})^\beta (l_t X_t)^{\theta-1} X_t = P_L q_t. \quad (45)$$

The law of motion of the costate  $q_t$  is the same as Eq. (23).

From Eqs. (44a) and (45),

$$\frac{\beta}{\theta} \left( \frac{l_t X_t}{h_t X_t - \bar{H}} \right) = \frac{P_H}{P_L}. \quad (46)$$

Thus in equilibrium,

$$\frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} = \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} \equiv \kappa. \quad (47)$$

By taking a time-derivative of the natural log of Eq. (71), we get

$$-\sigma \left\{ \beta \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} \right\} + (\beta - 1) \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t} + \frac{\dot{X}_t}{X_t} = \frac{\dot{q}_t}{q_t},$$

but from Eq. (47) and  $\beta + \theta = 1$ ,

$$\kappa = -\frac{1}{\sigma} \left( \frac{\dot{q}_t}{q_t} - g_t \right). \quad (48)$$

From Eq. (27),

$$\kappa = \frac{r - \rho}{\sigma}. \quad (49)$$

## Balanced growth under carbon tax

We attempt to find a trajectory along which the real interest rate  $r$  is constant. Call it "a generalized balanced growth (GBG) path".

From Eq. (16),

$$r = B_M F_1(k_t, 1) - \delta,$$

and thus  $k_t$  has to be constant in order for the real interest rate  $r$  to be constant.

In balanced growth,  $g_t$  is again assumed to be constant  $g$ . Then, along the GBG path, the budget constraint, Eq. (18), can be rewritten as

$$P_H h_t + P_L l_t = B_K F(k_t, 1) - (g + \delta) k_t. \quad (50a)$$

The right side of Eq. (50a) is constant. The left side of Eq. (50a), on the other hand, is not constant because, from Eq. (47),

$$\dot{h}_t = (\kappa - g) h_t - \frac{\bar{H}}{X_t} \kappa \quad (51a)$$

and

$$\dot{l}_t = (\kappa - g) l_t, \quad (52)$$

and inserting them into a time derivative of the left side of Eq. (50a) gives

$$P_H \dot{h}_t + P_L \dot{l}_t = (P_H h_t + P_L l_t) (\kappa - g) - \frac{\bar{H}}{X_t} \kappa. \quad (53)$$

Thus, for  $\bar{H} > 0$ , there exists no  $\kappa$  that makes the right side of Eq. (51a) zero unless  $g = 0$ . Therefore, the requirement of a constant real interest rate is incompatible with the system of differential equations that describes the competitive equilibrium.

## Output and employment

When  $\kappa = g$  and  $g > 0$ , Eq. (51a) is

$$P_H \dot{h}_t + P_L \dot{l}_t = -\frac{\bar{H}}{X_t} g \leq 0 \quad (54)$$

and the right side of Eq. (52) gradually approaches to zero. This implies, from Eq. (18), that in the competitive equilibrium, the growth of  $k_t$  is

$$P_H h_t + P_L l_t \geq B_K F(k_t, 1) - (g + \delta) k_t \Leftrightarrow \dot{k}_t \leq 0. \quad (55)$$

Both  $h_t X_t - \bar{H}$  and  $l_t X_t$  grow at the rate  $\kappa = g$ . Inserting this fact into Eq. (51a) gives

$$\dot{h}_t = -\frac{\bar{H}}{X_t} g. \quad (56)$$

Thus, the growth rate of output in high- $CO_2$ -emitting sector is

$$\begin{aligned} \frac{\dot{H}_t}{H_t} &= \dot{h}_t \frac{X_t}{H_t} + g \\ &= g \frac{H_t - \bar{H}}{H_t}. \end{aligned} \quad (57)$$

Similarly, from Eq. (52)

$$\dot{l}_t = 0. \quad (58)$$

Thus, the growth of output in low- $CO_2$ -emitting sector is

$$\frac{\dot{L}_t}{L_t} = g. \quad (59)$$

From Eq. (6), output of the high- $CO_2$ -emitting sector is

$$h_t = B_H N_t^H F(k_t, 1). \quad (60)$$

Taking a time derivative of Eq. (60) and solving it for  $\dot{N}_t^H$  gives

$$\dot{N}_t^H = \frac{\dot{h}_t}{B_{HF}(k_t, 1)},$$

and using Eq. (56), we get

$$\dot{N}_t^H = -\frac{\bar{H}}{X_t B_{HF}(k_t, 1)} g. \quad (61)$$

Similarly, from Eq. (6), output of the low- $CO_2$ -emitting sector is

$$l_t = B_L N_t^L F(k_t, 1). \quad (62)$$

Taking a time derivative of Eq. (62) and solving it for  $\dot{N}_t^L$  gives

$$\dot{N}_t^L = \frac{\dot{l}_t}{B_L F(k_t, 1)},$$

and using Eq. (58), we get

$$\dot{N}_t^L = 0. \quad (63)$$

Finally, from Eqs. (2), (61), and (63), the dynamics of employment in the capital-goods sector is

$$\begin{aligned} \dot{N}_t^K &= -\dot{N}_t^H - \dot{N}_t^L \\ &= \frac{\bar{H}}{X_t B_{HF}(k_t, 1)} g. \end{aligned} \quad (64)$$

## Carbon Tax in an imperfectly competitive environment

There is another case arising where a carbon tax is imposed on products in an imperfectly competitive environment.

One here could also assume that the price  $P_H$  is raised in imperfectly competitive markets and then the reallocation of production and employment from high to low carbon intensive goods could occur through relative prices:

$$\frac{\beta P_L}{\theta P_H} = \frac{h^* X_t}{l^* X_t} \quad (65)$$

As the price  $P_H$  is raised the relative share of high carbon intensity industries would decline. In this latter case the derivation of our baseline model of section 3 would hold. Only the relative prices of the two sectors would change through an environmental tax reform. In the latter case one can think, as in Boehringer, Loeschel, and Welsch (2008) that one has some tax incidence effect, where the tax is shifted forward and the demand for those products will react—reducing demand as a result of higher prices.<sup>5</sup>

We might also assume that instead of a carbon tax a cap and trade system with emission permits, that have to be bought and traded, can be established that would imply a cost on the carbon intensive activities.

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<sup>5</sup>Boehringer et al (2008) consider then also the differential demand change from domestic and foreign purchasers of the consumption good. They assume that for the taxed good there is a greater elasticity of demand abroad than a home.

## Carbon tax and wage subsidies

In either case, the competitive or imperfectly competitive environment, however, the tax revenue could be used to subsidize wage cost. This is the case of the German eco tax as discussed in our section with the literature review. case of the If in all sectors, the CO<sub>2</sub> high intensity as well as low intensity sectors, wages are subsidized, then the firms can employ labor at a lower cost than the marginal product of labor. Using our production function above and assuming, as also above presumed, that the production is the same for all sectors, then we might write:

$$(1 - \tau)\omega = (1 - \alpha)\left(\frac{K}{N}\right)^\alpha \quad (66)$$

with  $\tau$  a subsidation rate for the real wage  $\omega$  and the right hand side of the above equation representing the marginal product of labor at the employment level  $N$ . Inverting the above function on the right hand side of the equation gives us,

$$\bar{N} = \frac{K}{(1 - \tau)\omega/(1 - \alpha)} \quad (67)$$

Thus,  $\bar{N}$  will increase with wage subsidies and it will be higher the higher the subsidy  $\tau$  is. We will thus have always  $\bar{N} > N$ , whereby  $N$  is the labor employed in the case when wages are not subsidized.

In this version of our model we would have thus a reduction of employment in the carbon intensive sector and an overall increase in employment due to the use of the tax revenue to subsidize real wages across the board.

Yet, two remarks are appropriate. First, the extent to which output and employment in the carbon intensive sector would fall— and thus the carbon intensive sector reduced— would actually depend on the strength of the first effect as compared to the second effect. Thus, the carbon intensive sector (and the emission there) could rise or fall. Also, depending on those two effects, total aggregate employment could rise or fall.

Second, one could argue that one might want to subsidize wages in the two sectors in a differential way, for example, subsidizing wages only in the less carbon intensive sector, and less so – or not subsidizing – the emission intensive sector. Yet, this would not be acceptable for unions, representing employees in the two different sectors.

So, overall, this policy measure resulting from our second model version would be more of interventionist type than from our baseline model of section 3. Though it seems to be currently already frequently employed it appears to us less efficient than the policy recommendation resulting from the next version of our model.

## 4 Preferences, Carbon Tax and Product Subsidies

The next version allows for taxation and subsidies of sector simultaneously. Suppose that an environmental policy through which an each agent must give up a positive amount of high- $CO_2$ -emitting goods  $\bar{H}$  but in return it receives the amount of low- $CO_2$ -emitting goods  $\bar{L}$  equal in value to the value of the goods  $\bar{H}$  given up. This requires that

$$P_L \bar{L} - P_H \bar{H} = 0. \quad (68)$$

We assume that  $\bar{H}$  and  $\bar{L}$  are strictly positive.

Due to this policy, the utility function is rewritten as

$$U_t = \int_0^\infty e^{-\rho t} \frac{\left[ (h_t X_t - \bar{H})^\beta (l_t X_t + \bar{L})^\theta \right]^{1-\sigma} - 1}{1-\sigma} dt. \quad (69)$$

### Consumption under carbon tax and product subsidies

The agent's problem is to

$$\max_{h_t, l_t} \text{Eq. (69)}$$

subject to Eq. (18), for given  $k_0 > 0$ .

The new Hamiltonian is

$$\Omega_t \equiv \frac{\left[ (h_t X_t - \bar{H})^\beta (l_t X_t + \bar{L})^\theta \right]^{1-\sigma} - 1}{1-\sigma} + q_t [B_K F(k_t, 1) - P_H h_t - P_L l_t - (\delta + g_t) k_t]. \quad (70)$$

The first-order necessary conditions are

$$[\cdot]^{-\sigma} \beta (h_t X_t - \bar{H})^{\beta-1} (l_t X_t + \bar{L})^\theta X_t = P_H q_t, \quad (71)$$

and

$$[\cdot]^{-\sigma} \theta (h_t X_t - \bar{H})^\beta (l_t X_t + \bar{L})^{\theta-1} X_t = P_L q_t. \quad (72)$$

The law of motion of the costate  $q_t$  is the same as Eq. (23).

From Eqs. (71) and (72),

$$\frac{\beta}{\theta} \left( \frac{l_t X_t + \bar{L}}{h_t X_t - \bar{H}} \right) = \frac{P_H}{P_L}. \quad (73)$$

Thus in equilibrium,

$$\frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t + \bar{L}} = \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} \equiv \kappa. \quad (74)$$

By taking a time-derivative of the natural log of Eq. (71), we get

$$-\sigma \left\{ \beta \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t + \bar{L}} \right\} + (\beta - 1) \frac{\dot{h}_t X_t + h_t \dot{X}_t}{h_t X_t - \bar{H}} + \theta \frac{\dot{l}_t X_t + l_t \dot{X}_t}{l_t X_t + \bar{L}} + \frac{\dot{X}_t}{X_t} = \frac{\dot{q}_t}{q_t},$$

but from Eq. (74) and  $\beta + \theta = 1$ ,

$$\kappa = -\frac{1}{\sigma} \left( \frac{\dot{q}_t}{q_t} - g_t \right). \quad (75)$$

From Eq. (27),

$$\kappa = \frac{r - \rho}{\sigma}. \quad (76)$$

## Balanced growth under carbon tax and product subsidies

We find again a GBG path along which the real interest rate  $r$  is constant.

From Eq. (16),

$$r = B_M F_1(k_t, 1) - \delta,$$

and thus  $k_t$  has to be constant in order for the real interest rate  $r$  to be constant.

Then, along the GBG path, the budget constraint, Eq. (18), can be rewritten as

$$P_H h_t + P_L l_t = B_K F(k_t, 1) - (g + \delta) k_t. \quad (77)$$

The right side of Eq. (77) is constant; on the other hand,  $h_t$  and  $l_t$  on the left side of Eq. (77) are not constant but from Eq. (74),  $h_t X_t - \bar{H}$  and  $l_t X_t + \bar{L}$  are constant.

However, under our environmental policy Eq. (68), we may rewrite Eq. (73) as

$$P_L l_t X_t = \frac{\theta}{\beta} P_H h_t X_t - \frac{1}{\beta} P_H \bar{H}. \quad (78)$$

Inserting Eq. (78) into the budget constraint Eq. (77) gives

$$\frac{1}{\beta} P_H (h_t X_t - \bar{H}) = [B_K F(k_t, 1) - (g + \delta) k_t] X_t. \quad (79)$$

## Output and employment

In balanced growth, from Eq. (79), both  $h_t X_t - \bar{H}$  and  $l_t X_t + \bar{L}$  grow at rate  $g$ , i.e.,  $\kappa = g$ . Inserting this fact into Eq. (74) gives

$$\dot{h}_t = -\frac{\bar{H}}{X_t} g. \quad (80)$$

Thus, the growth rate of output in high- $CO_2$ -emitting sector is

$$\begin{aligned} \frac{\dot{H}_t}{H_t} &= \dot{h}_t \frac{X_t}{H_t} + g \\ &= g \frac{H_t - \bar{H}}{H_t}. \end{aligned} \quad (81)$$

Similarly, from Eq. (74)

$$\dot{l}_t = \frac{\bar{L}}{X_t} g. \quad (82)$$

Thus, the growth of output in low- $CO_2$ -emitting sector is

$$\begin{aligned} \frac{\dot{L}_t}{L_t} &= \dot{l}_t \frac{X_t}{L_t} + g \\ &= g \frac{L_t + \bar{L}}{L_t}. \end{aligned} \quad (83)$$

From Eq. (6), output of the high- $CO_2$ -emitting sector is

$$h_t = B_H N_t^H F(k_t, 1). \quad (84)$$

Taking a time derivative of Eq. (84) and solving it for  $\dot{N}_t^H$  gives

$$\dot{N}_t^H = \frac{\dot{h}_t}{B_H F(k_t, 1)},$$

and using Eq. (80), we get

$$\dot{N}_t^H = -\frac{\bar{H}}{X_t B_H F(k_t, 1)} g. \quad (85)$$

Similarly, from Eq. (6), output of the low- $CO_2$ -emitting sector is

$$l_t = B_L N_t^L F(k_t, 1). \quad (86)$$

Taking a time derivative of Eq. (86) and solving it for  $\dot{N}_t^L$  gives

$$\dot{N}_t^L = \frac{\dot{l}_t}{B_L F(k_t, 1)},$$

and using Eq. (82), we get

$$\dot{N}_t^L = \frac{\bar{L}}{X_t B_L F(k_t, 1)} g. \quad (87)$$

Finally, from Eqs. (2), (85), and (87),

$$\begin{aligned} \dot{N}_t^K &= -\dot{N}_t^H - \dot{N}_t^L \\ &= \frac{\bar{H}}{X_t B_H F(k_t, 1)} g - \frac{\bar{L}}{X_t B_L F(k_t, 1)} g. \end{aligned} \quad (88)$$

However, from Eq. (9) and our environmental policy (68),

$$\frac{\bar{H}}{\bar{L}} = \frac{B_H}{B_L}.$$

Thus, plugging this into Eq. (88) gives the dynamics of employment in the capital-goods sector

$$\dot{N}_t^K = 0. \quad (89)$$

## 5 Empirical Analysis

Next, we want to undertake an empirical analysis of some variants of the model as above proposed. We also will pursue an empirical analysis to study the potential impact of climate policies, as suggested in the previous sections, on employment and output.

### 5.1 Data Description and Modeling Approach

For our empirical analysis we employ a German data set to identify high and low carbon intensive industries. Based on the German industry classification, we use data from the EU Klems database (<http://www.euklems.net/index.html>) of nine countries to estimate a linear dynamic model in form of a vector autoregression (VAR) for employment and output from high- and low-carbon sectors of the economy.

We use data from German input-output tables (1995) to exemplarily generate the two sectors, high carbon-intensive sector (HCIS), and low carbon intensive sector (LCIS). German input-output tables are provided by the Federal Statistical Office ("Statistisches Bundesamt") and are available at a 71 sector level. In addition to traditional input-output tables, the German Federal Statistical Office prepares energy input-output tables which track the flow of natural resources into the economic circuit and the emission of pollutants and other substances out of the economic circuit into the natural environment.

The energy input-output tables for 1995 specify the total  $CO_2$  emission in kilo tons for each sector. With these data, we could calculate several ratios in order to indicate the  $CO_2$ -intensity of each sector. We mainly used the ratio of  $CO_2$  in kilo tons over gross output in million euros ("direct  $CO_2$  output-intensity"). This ratio describes how many kilo tons of  $CO_2$  emissions a specific sector in the economy requires in order to generate one million Euro of gross output. We can interpret the reciprocal of  $CO_2$  output-intensity as  $CO_2$  productivity since it indicates how much gross output a sector can generate with one kt emitted  $CO_2$ . With the help of these key figures, we can now rank different sectors according to their  $CO_2$  intensity.

Of course, other key ratios may be computed and may provide different types of information. For example, we might be interested in the  $CO_2$  emission per job in the different sectors of the economy (" $CO_2$  labor intensity"), or conversely the number of jobs that a sector can sustain or generate by emitting one kilo ton of  $CO_2$ . Another ratio of interest might be the amount of  $CO_2$  emitted per unit value added. We also calculated total  $CO_2$  (output) intensities for each sector which take into account the accumulated  $CO_2$  emitted by the inputs of a sector. From a theoretical point of view, this latter measure of  $CO_2$  intensity seems most appealing. The ranking of "good" and "bad" sectors turns out to be sensitive to different measures even though the ranking does not completely change for the most part. As a first step of our empirical analysis, we decided to use direct  $CO_2$  output intensity to rank the 71 sectors. A table with the high and low intensive sector can be found in the appendix (...).

We classify industry sectors in the two sector groups (HCIS and LCIS). Industry sectors whose

carbon intensity per unit of output is above (below) the median are classified as belonging to the high-carbon intensity (low-carbon intensity) sector. Note that this grouping has been done on basis of the German  $CO_2$  intensity data (1995), i.e. the ranking of industries is identical for all countries analyzed. The absolute level of  $CO_2$  emissions as well as the absolute  $CO_2$  intensity in a particular sector may of course differ among countries. This depends on the size of the industry, the technology used, the energy mix and possibly on other factors. However, the relative position of an industry within a country can be expected to be roughly the same, especially among industrialized countries. Thus, energy intensive manufacturing industries like metals, coke, mechanical wood and can be expected to be relative high carbon intensive in any country. Since we have just two sectors (HCIS and LCIS), only changes in  $CO_2$  intensities of industries around the median have an effect on the composition of the HCIS and LCIS in a country.

We specify a first-order, four-variable VAR model comprising high-carbon intensity output, denoted by  $OUT_{hi,t}$ , low-carbon intensity output ( $OUT_{lo,t}$ ), high-carbon intensive employment ( $EMP_{hi,t}$ ) and low-carbon intensive employment ( $EMP_{lo,t}$ ). All variables in the VAR are specified in terms of annual growth rates (i.e., log-differences) and collected in a vector  $y_t$ , defined by

$$y_t = \begin{bmatrix} out_{hi,t} \\ out_{lo,t} \\ emp_{hi,t} \\ emp_{lo,t} \end{bmatrix} = \begin{bmatrix} \log OUT_{hi,t} - \log OUT_{hi,t-1} \\ \log OUT_{lo,t} - \log OUT_{lo,t-1} \\ \log EMP_{hi,t} - \log EMP_{hi,t-1} \\ \log EMP_{lo,t} - \log EMP_{lo,t-1} \end{bmatrix} \times 100$$

Table 5 shows some summary statistics of the data.

Table 1: Summary Statistics (Germany)

	$out_{hi,t}$	$out_{lo,t}$	$emp_{hi,t}$	$emp_{lo,t}$
Mean	2.17	3.07	-0.24	0.42
$out_{hi,t}$	3.99	2.31	0.91	1.48
$out_{lo,t}$	0.74	2.42	0.71	1.19
$emp_{hi,t}$	0.44	0.45	1.03	0.86
$emp_{lo,t}$	0.67	0.69	0.77	1.21

Bottom panel: Variances (diagonal elements), covariances (above-diagonal elements), and correlations (below-diagonal elements)

The first-order VAR is of the form

$$y_t = c + Ay_{t-1} + \varepsilon_t, \quad (90)$$

with disturbances  $\varepsilon_t$  satisfying  $E(\varepsilon_t) = 0$ , and

$$\text{Cov}(\varepsilon_t, \varepsilon_s) = \begin{cases} \Sigma, & t = s, \\ 0, & t \neq s, \end{cases} \quad (91)$$

and  $c$  and  $A$  being a constant parameter vector and matrix, respectively, and  $\varepsilon_t$  denoting the one-step-ahead prediction error. The parameter estimates are as follows:

$$\hat{c}_{GER} = \begin{bmatrix} 0.81 \\ 1.19 \\ -0.61 \\ -0.86 \end{bmatrix}, \quad \hat{A}_{GER} = \begin{bmatrix} -0.20 & 0.69 & -0.24 & -0.48 \\ -0.19 & 0.76 & -0.38 & -0.12 \\ -0.20 & 0.36 & 0.29 & -0.04 \\ -0.22 & 0.66 & 0.25 & -0.26 \end{bmatrix}, \quad \hat{\Sigma}_{GER} = \begin{bmatrix} 3.03 & 1.56 & 0.30 & 0.92 \\ 1.56 & 1.63 & 0.25 & 0.59 \\ 0.30 & 0.25 & 0.14 & 0.23 \\ 0.92 & 0.59 & 0.23 & 0.54 \end{bmatrix}.$$

With the eigenvalues of  $\hat{A}_{GER}$  being  $0.4698 \pm 0.2444i$  and  $-0.1739 \pm 0.1149i$  and the moduli being 0.5296 and 0.2085, the estimated system is stable.

Clearly, in view of the the data limitations, higher than first-order VARs cannot be estimated. However, given that we work with annual data, a first-order VAR should be sufficient for a principal approximation of the employment-output dynamics.

We continue the analysis here with the German data. The statistics and estimates for all other countries are provided in the appendix.

## 5.2 Policy-Response Analysis

To investigate dynamic dependencies among the variables and to assess the consequences of policy measures we conduct a response analysis with the estimated model. Specifically, we derive impulse-responses as well the responses to specific policy measures. The policy measures at hand are a tax on the consumption of high-carbon intensive goods and a subsidy on the consumption of low-carbon intensive goods.

Impulse response functions generally indicate how the endogenous variables respond to external influences. In a VAR model, where all variables are endogenous, the only external inputs are the disturbances, which amount to one-step-ahead prediction errors. They are “innovations” or “surprises,” such as “policy shocks,” which cannot be explained by the model and past data. We translate the instrument of a carbon tax into a negative growth shock for the HCIS while a subsidy for the LCIS is interpreted as a positive growth shock to all industries in this sector.

Using the lag operator,  $L$ , defined by  $Ly_t = y_{t-1}$ , we can express the VAR process (90) as  $A(L)y_t = \varepsilon_t$ ,<sup>6</sup> with  $A(L) = I - AL$ . The infinite moving average representation, given by

$$y_t = A^{-1}(L)\varepsilon_t = \tilde{C}(L)\varepsilon_t, \quad \text{Cov}(\varepsilon_t) = \Sigma,$$

captures the responses of the  $y$ -variables with respect to the prediction errors,  $\varepsilon_t$ . Here,  $\tilde{C}(L) = \tilde{C}_0 + \tilde{C}_1L + \tilde{C}_2L^2 + \dots$  is, in general, a matrix polynomial of infinite order.<sup>7</sup> The  $i, j$ -element of  $\tilde{C}_k$ ,  $\tilde{c}_{k,ij}$ , can be interpreted as the change in the  $i$ -th component in  $y_{t+k}$  due to a unit shock in the  $j$ -th innovation in vector  $\varepsilon_t$  at time  $t$ .

However, the prediction error  $\varepsilon_{jt}$  is not necessarily uniquely associated with a shock to  $y_{jt}$  in the same period. To have a unique association we have to make sure that the shocks are uncorrelated.

<sup>6</sup>To simplify the notation, we omit the constant term,  $c$ , as it does not enter the dynamics of the process.

<sup>7</sup>We use superscript  $\varepsilon$  to refer to response coefficients and with respect to the prediction error.

In linear VAR analysis, this can be achieved by regarding  $\varepsilon_t$  as being some linear combination of “structural” shocks, denoted by  $u_t$ , such that

$$\varepsilon_t = Ru_t. \quad (92)$$

A common strategy is to obtain the Choleski decomposition of the covariance matrix of the prediction errors,  $\Sigma$ , i.e.,

$$\Sigma = RR',$$

where  $R$  is a lower triangular matrix with positive diagonal elements. Transformation  $u_t = R^{-1}\varepsilon_t$  is also called an *orthogonalization* of the prediction errors, because the components of  $u_t$  are uncorrelated and have unit-variance, i.e.,  $\text{Cov}(u_t) = I$ , since

$$\text{E}(u_t u_t') = \text{E}[R^{-1}\varepsilon_t \varepsilon_t' R^{-1}] = R^{-1}\Sigma(R^{-1})' = I.$$

Interpreting vector  $u_t$  as the structural innovations driving the process, i.e.,

$$y_t = \tilde{C}(L)\varepsilon_t = \tilde{C}(L)Ru_t = C(L)u_t.$$

the *structural impulse response function* can be derived from the moving average coefficients by

$$C_k = \tilde{C}_k R. \quad (93)$$

Note that the derivation of the structural shocks,  $u_t$ , via Choleski decomposition places specific assumptions on the contemporaneous influence of the structural shocks on the endogenous variables. In our specification, with ordering  $y_t = (\text{out}_{hi,t}, \text{out}_{lo,t}, \text{emp}_t)'$ , a lower-triangular  $R$  implies that structural shocks to high-energy output immediately affects high-energy, low-energy and aggregate employment. A shock to the low-energy sector has, however, no simultaneous impact on the high-energy sector, which reacts only with a delay of one period, but has an immediate affect on aggregate employment.

Our estimates for VAR-coefficient matrix  $A$ , given above, and  $R$ ,

$$\hat{R} = \begin{bmatrix} 3.55 & 0 & 0 \\ 0.77 & 1.03 & 0 \\ 0.03 & 0.48 & 0.76 \end{bmatrix}$$

give rise to the impulse responses,  $\hat{C}_k, k = 0, 1, \dots, 10$ , shown in Figure 1. Clearly, in view of the small sample size, the results reported here can only be indicative. Interval estimation and significance testing, prevented by sample-size limitations, would be required for more definite conclusions. However, rather than producing erratic responses, as is often the case if the number estimated parameters is very high relative to the number of observations, response analysis discussed below yields smooth and plausible response estimates.

The plots indicate that all endogenous variables respond to impulses over a period of about five years at most, after which they decay to zero. In the following, we briefly discuss the point estimates of the unit-impulse responses, i.e., the responses due to positive growth shocks with a size of one percent.

For a one-percent-shock to the high-carbon intensive sector we have the following responses. It has only an immediate impact to the sector itself; there is virtually no effect after one year and beyond. The low-carbon intensive also experiences a simultaneous benefit in that it grows by 0.2%, an effect that also decays after one year. Aggregate employment drops minimally after one year by somewhat less than 0.1%; this negative employment growth vanishes after three years.

A shock to the low-energy sector has, due the identification restrictions in place, no immediate impact on the high-carbon intensive sector, but causes the high-carbon intensive sector to grow by one percent after a year and virtually no effect after that. The impact on the low-carbon intensive sector itself remains positive for the first two years after which it vanishes. Aggregate employment growth by 0.5% within the same year of the shock, by 1% after one year. The positive response drops to zero at year four and thereafter.

A shock to employment lowers output growth in the high-carbon intensive (low-carbon intensive) sector by about 1% (0.6%) after one year. The negative consequences disappear after three (four) years. After the initial shock, employment growth itself becomes slightly negative during the following three years and zero thereafter.

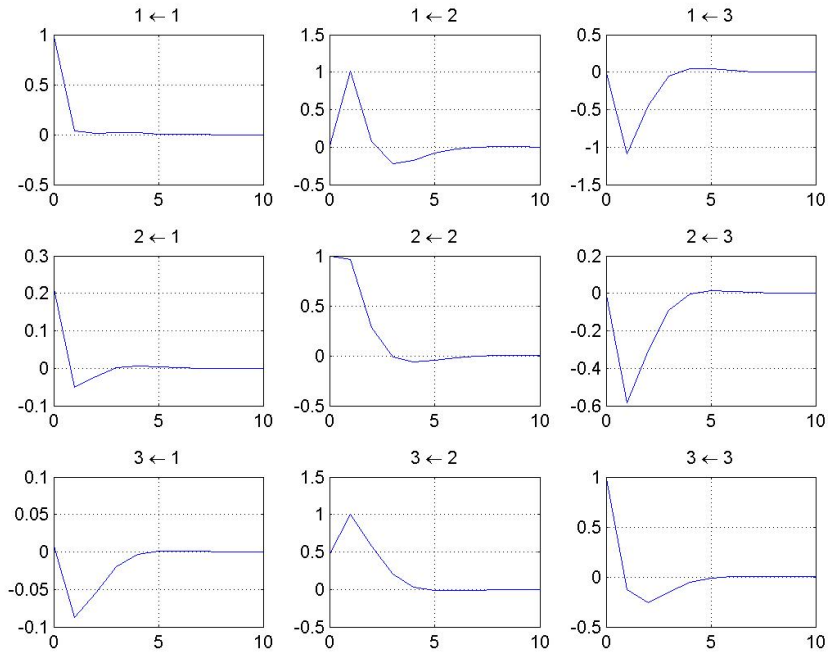


Figure 1: Impulse-response functions from the estimated VAR(1)model (90) with  $y_t = (out_{hi,t}, out_{lo,t}, emp_t)'$ . The graph with heading “ $i \leftarrow j$ ” shows the response of the  $i$ th variable in  $y_t$  due to an unit impulse to structural shock  $j$ .

To assess the cumulative effects, Figure 2 shows the cumulative-response functions, computed

by

$$\bar{C}_k = \sum_{i=0}^k C_i.$$

The cumulative long-term effect of a one-percent shock to high-carbon intensive sector growth are as follows. The cumulative response of the high-carbon intensive sector itself remains virtually at the initial shock level; the low-carbon intensive sector experiences small positive growth of about 0.15%; and aggregate employment is negatively affected by about -0.15%. A shock to the low-carbon intensive growth induces cumulative high-carbon intensive growth of about 0.6%; the low-carbon intensive sector responds more strongly with an increase over 2.1%; and the aggregate employment growth increases by about 2.2%. Finally, the cumulative long-term effects of an employment shock are a roughly 1.5% (1%) drop in high-carbon intensive (low-carbon intensive) growth, and a 0.4% increase in aggregate employment.

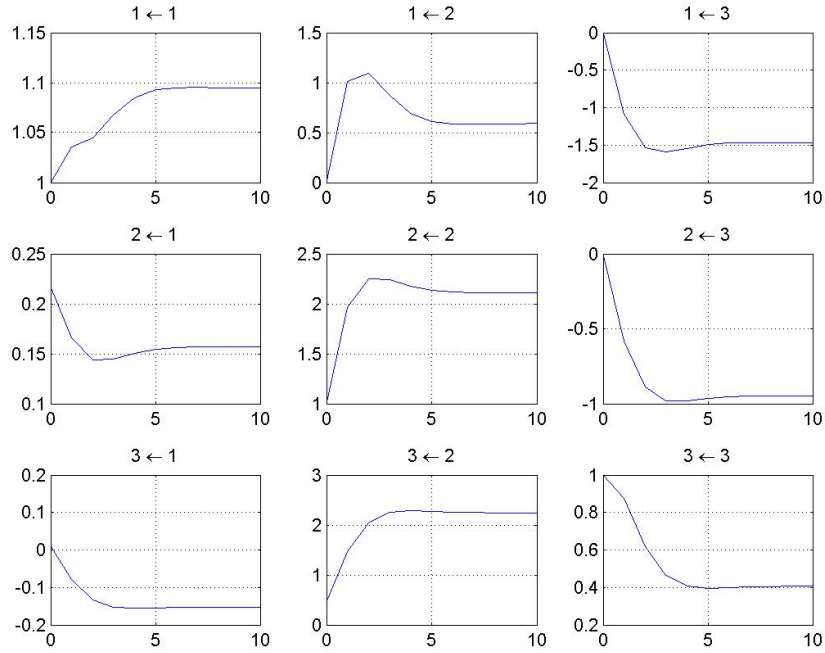


Figure 2: Cumulative-response functions from estimated VAR(1)model (90) with  $y_t = (out_{hi,t}, out_{lo,t}, emp_t)'$ . The graph with heading “ $i \leftarrow j$ ” shows the response of the  $i$ th variable in  $y_t$  due to an unit impulse to structural shock  $j$ .

We are interested in a particular policy shock which combines a positive shock to low-energy sector by granting, for example, some form subsidies or tax relief, with a negative shock to the high-carbon intensive sector by a reduction of existing subsidies or by imposing additional taxes, such that the latter finances the former. Specifically, we calculate the cumulative effects on aggregate employment shifting five billion Euro from the high- to the low-energy sector—a sum that amounts to roughly one tenth of a percent of aggregate output at the end of our sample.

The cumulative effect of such a combined shock on aggregate employment, as shown in Figure

3, is positive. Employment growth by close to 0.1% in the same year, close to 0.3% within one year, and at about 0.43% after three years.

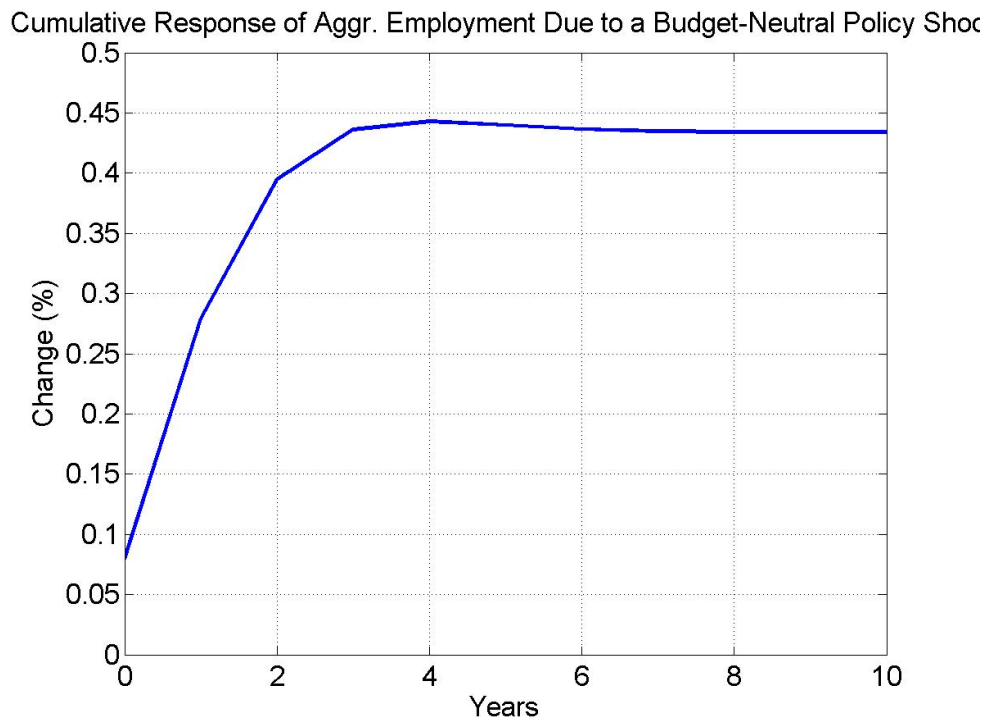


Figure 3: Cumulative-response of aggregate employment due to an instantaneously growths-neutral policy shock.

The question is whether the positive effect on employment from a budget-neutral reallocation from the high- to the low-carbon intensive sector is accompanied by a long-run drop in overall output. This, however, is not the case, as the cumulative joint response estimates (shown in Figure 4) indicates. Output drops initial by about 0.1%, but increases within two years by 0.3% to stabilize at about 0.18% after five years.

In summary, our response analysis suggest that budget-neutral green policies, which favor Germany's low-carbon intensive sector at the expense of the high-carbon intensive sector, result both in employment and output growth.

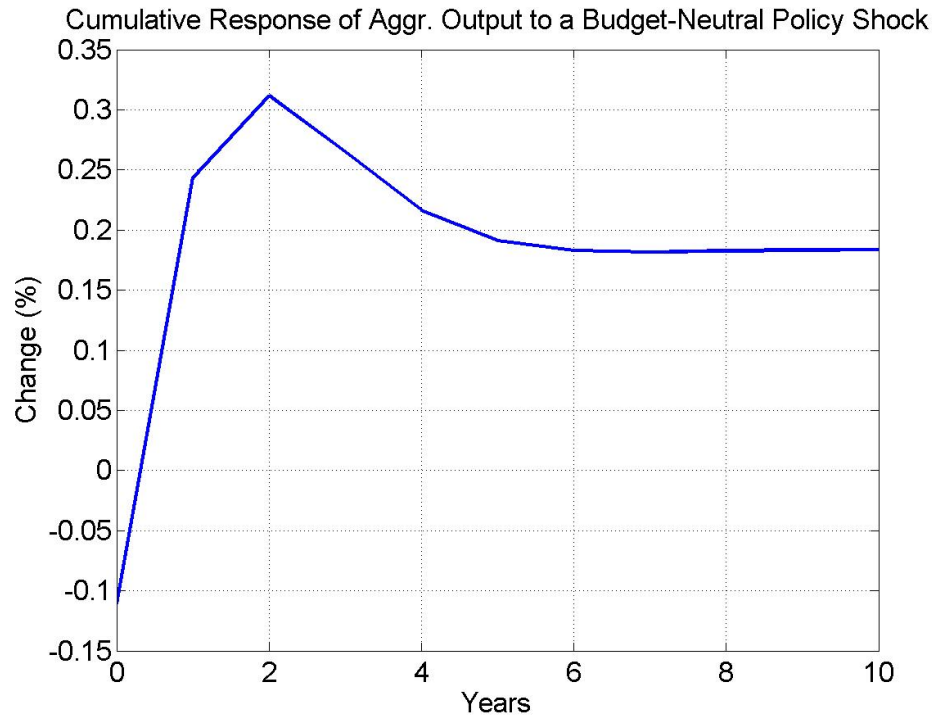


Figure 4: Cumulative response of aggregate output due to an instantaneously growths-neutral policy shock.



## 6 Discussion of the Literature

The main issues in the literature are what type of policy instruments should be applied to reduce carbon emission and what employment effect various policies will have. As to the latter, often the position has been put forward that a proper policy could entail a double dividend.

### 6.1 The Issue of Policy Instruments

The literature does generally not discuss changing preferences and structural change as means to combat climate change. The scope of the analysis is on regarding emissions as an externality that have to be internalized to achieve a more efficient social outcome. The question of possible employment (side) effects then arises as a secondary issue. It is not always clear where to draw the line between environmental policies in general and climate policies in particular. In the context of climate policies, the economic literature mainly concentrates on policies to reduce GHG's and primarily  $CO_2$ . A tax on carbon as a means to reduce  $CO_2$  emissions has been suggested by economists for quite some time (see Pearce (1991)). Alternatively, a cap-and-trade system could be implemented through which the right to emit  $CO_2$  would be priced. The literature mainly discusses these two approaches:

**Tradable permits** (Cap-and-trade system) require that the actual polluter can be identified, for example firms. Enforcement of the cap is difficult and trading of emission certificates are exposed to speculative investments, generating a high volatility of the carbon price as the European example shows. According to an estimate by Nell, Semmler, and Rezai (2009) the carbon price, in case of emission trading, is even ten times more volatile than stock prices, which are already about seven times more volatile than the GNP.

A **Carbon Tax**, on the other hand, allows for a broader application, including energy supply, major polluting industries, the service sector, transport system and households. Furthermore, the generated tax revenue can be used to reduce other taxes, and tax funds can be used to compensate developing economies, or can be used to induce climate-friendly investment behavior (see Uzawa (2003)).

Although economists seem to lean toward the carbon tax, policy makers appear to tend toward the market-based cap-and trade system. They argue that for politicians it is difficult to announce the increase of tax rates when they run for public offices.

In this context we have mainly pursued policies that employ a carbon tax. We have not considered the cap-and trade system. We want to refer to the literature here, that hints at the experience of the European Union with emission trading that seems to demonstrate that there are clear advantages in choosing carbon taxes over carbon trading schemes. The advantages are the universal applicability, better efficacy, and lower set-up costs due to existing administrative institutions. The disadvantages of carbon trading are the arbitrary distribution of rights to special interest groups and the disproportionate volatility of the emission price due to uncertainty in the overall quota and financial arbitrage. The introduction of carbon taxes in developed countries appears to be not only useful to meet the commitments of the Kyoto protocol, but also allows for some redistribution of

revenues to developing countries.

The academic literature on growth and climate change finds similar results as in the growth literature regarding with respect to government actions, as for example in Greiner and Semmler (2007), Greiner and Semmler (2008) and Greiner, Gruene, and Semmler (2009). A zero emission tax is not necessarily welfare improving (see Greiner and Semmler (2008)). The results obtained in this work is in line with the position of the above mentioned economic studies (Uzawa, Nordhaus, Mankiw, IPCC, 2007) on the carbon tax which is, as above stated, preferable to a cap-and-trade system.

## 6.2 The Issue of the Double Dividend

Once one has decided to implement one kind of climate policies, the question arises which effects such a policy may have on the employment of an economy. Economists have even been wondering if correcting for environmental externalities can not at the same time generate additional employment - the so called "double dividend hypothesis". The question of a possible double dividend is very complex and not only depends on the direct effects that climate (or environmental) policies have on the economic system but also on the state and conditions of the particular labor markets under investigation. A simple one dimensional answer should therefore not be expected.

In our approach, we address the question of employment indirectly. The driving force in our model are preferences and changing demand to induce a structural change. We consider three policy measures to impinge or accelerate the structural change: A carbon tax, a carbon tax and wage subsidies, and a carbon tax and tax subsidies. We avoid a discussion about unemployment and possible economic mechanisms on the labor markets by assuming a competitive labor market. Our main point is that the total level of employment will depend on the employment levels of the H and the L sector and these employment levels will positively correlate with the relative sizes of these sectors. Certainly, different assumptions about the institutional environment on the labor markets and the economic mechanisms at work may lead to different effects. However, our empirical analysis with German data suggests that - independently of the "true" labor market model - a slightly positive effect on employment can be expected from a combined carbon tax / carbon subsidy.

A very broad spectrum of literature on environmental policies and their employment effects exists. We concentrate here on major studies that discuss environmental policies that are or can be considered climate policies. Furthermore, since our own study is oriented towards empirical results, we confine ourselves to those studies that report some empirical or simulation results.

We are not aware of any studies that discuss the employment effects of cap-and-trade-systems. This might be due to limited practical experience we have with cap-and trade-systems, as compared to tax schemes.

Some EU countries introduced environmental tax reforms in the past years. Most notably, Germany implemented its so called "ecological tax reform" in 1998, through which an energy tax was introduced and the tax revenue was used to subsidize wage cost. The main idea of the ecological

tax reform is expressed in a paper by Weizsäcker (1992). Here the view is taken that when economies exhibit an overuse of energy (with intensive  $CO_2$  emission) but an underemployment of the labor force, an energy (emission) tax could be introduced to subsidize wage cost so that employment becomes cheaper and more of the available labor force can be employed. This is in principle the argument of the double dividend of an environmental tax scheme, where an externality is removed and employment is increased at the same time.

Through overuse of energy, advanced economies have become dependent on a scarce resource (mostly generated from fossil fuel), creating high  $CO_2$  emissions. It is worthwhile reducing the use of this type of energy and by an environmental tax and subsidizing labor (see von Weizsäcker and Jesinghaus (1992) and Bleischwitz and von Weizsäcker (1999)). Other countries have now made a similar attempt to move into this direction as well.<sup>8</sup> This is explained as "a push toward sustainability and resource productivity" (Weizsäcker, 1992:42). Indeed, such a tax would impose a tax on energy (emission) intensive sectors and reduce labor cost, the latter promoting employment.

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The "ecological tax reform 1998" in Germany was partly based on these ideas of von Weizsäcker and others and gave reason to conduct several studies on the employment effects of the implemented policy measures. The most comprehensive studies were carried out by Bach, Bork, Kohlhaas, Lutz, Meyer, Praetorius, and Welsch (2001) and Frohn, Chen, Hillebrand, Lemke, Lutz, Meyer, and Pullen (2003). The first study was conducted by the German Institute for Economic Research (DIW) on behalf of the German Federal Ministry of Finance ("Bundesministerium für Finanzen"). Both studies employ simulation models (PANTA RHEI, model system of RWI). The PANTA RHEI model is an econometric model for the German economy. It is a detailed multisectoral model covering 58 industrial branches. In PANTA RHEI, all parameters are estimated by econometric methods using time series of the input-output tables of the German economy. The model has a disaggregated energy and air pollution module. It is built for medium-term forecasts up to 2020. The methodology of PANTA RHEI including empirical results is also discussed in detail by Meyer, Bockermann, Ewerhard, and Lutz (1999) and Meyer (2005). Lutz and Meyer (2008) provide an overview of empirical studies about the effects of the German tax reform that have been conducted over the last years.

Strictly speaking, the German ecological tax reform was not exclusively targeted at achieving climate goals but was thought to serving environmental and energy efficiency goals in general. Consequently, the cited studies analyze a broad variety of economic effects, not only employment. Nevertheless, we can gain some valuable insights on the employment effects of the policy measures, in particular since the tax reform was heavily promoted under the double dividend hypothesis. Germany's ecological tax reform basically boiled down to the introduction of energy taxes and a constant increase of the at that time already existing petroleum tax. The tax revenue has been used to subsidize social security contributions which are levied on labor thereby reducing the effective wage cost. However, large exceptions from the energy tax exist for energy intensive industries and air traffic.

The study by Bach et al. (2001) concludes that the eco tax will reduce Germany's growth only

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<sup>8</sup>See Sweden, France and recently also the US under the Obama administration

<sup>9</sup>As Weizsäcker states: "Ecological tax reform involves a shift from direct taxes on labor to indirect taxes on energy." (Weizäcker, 1992:43)

slightly (-0,1 percent) but will have a positive effect on employment and reduce  $CO_2$  emissions. However, the latter two effects are also rather small and by no means sufficient to solve either the problem of climate change nor the problem of high unemployment in Germany. Due to these relative small effects, some economists have titled the German reform as an "eco-political fig leaf" (see Boehringer and Schwager (2003)).

The simulation of different scenarios in Frohn, Chen, Hillebrand, Lemke, Lutz, Meyer, and Pullen (2003) confirm the results of Bach et al. (2001). All scenarios resulted in slightly positive employment effects and a small reduction of emissions. While the employment increase did not react very strongly to an increase in the tax rates and the abolishment of the eco tax exceptions,  $CO_2$  emissions fell stronger in scenarios with higher tax rates and no exceptions from the eco tax. The highest reduction of  $CO_2$  emissions was achieved in a scenario with a hypothetical  $CO_2$  tax (as opposed to an energy tax). However in this scenario, the still positive employment effect was the weakest and the decelerating effect on macroeconomic activity was the strongest. A switch from the current energy taxation to a  $CO_2$  tax is endorsed by most authors. Besides different findings and criticism about the size of the "double dividend" in the case of the German experiment, we can at least conclude that no cumulative negative effects on employment were found.

Several reviews of studies about the employment effects of environmental policies have been prepared by the OECD over the last decades (OECD, 1978), (OECD, 1997), and (OECD, 2004). In addition to the analysis of general environmental policies, the OECD also reviews the evidence of employment effects related to climate policies of OECD countries in its 2004 report. In accordance to our approach, the OECD sees a general tendency of increased employment in certain sectors of OECD economies due to a change in the demand structure: "On the other hand, a significant number of environment-related new jobs results from a change of business attitudes as well as of consumers preferences and demand for a cleaner environment" (OECD, 2004).

The OECD distinguishes "bottom-up" approaches in which specific policies have been implemented at the local level ("territorial initiatives") from so called "top-down" approaches in which macro-economic policy is implemented at the "top" level of policy makers and institutions. Bottom-up approaches exist in a variety of forms and have in common that they are pursued by different *local* actors (public or private) and take local or regional peculiarities into account. Only scarce data is available on the employment and environment impacts of the initiatives identified in the OECD study. The results remain therefore unclear on a general level (see OECD (2004)). With respect to the bottom-up approaches the OECD concludes that territorial initiatives are not a universal panacea for challenges in regional development, employment, social inclusion and environment and that they are no alternative to the traditional top-down approach to employment and environmental policy but rather a supplement. In order to fight climate change, a coordination of policies is obviously necessary so that top down approaches seem to be the more appropriate answer to reduce climate change.

In the discussion of the top-down models, the OECD study reviews different models and draws some conclusions on the double dividend hypothesis(see OECD (2004)). Generally, the extent to which a double dividend may be earned through environmental taxes depends largely on the already existing tax system of an economy. The interaction of environmentally related taxes with other taxes (for example replacement or reduction of taxes on labor through energy taxes) may than in total have a positive effect on employment. The OECD also points out that the current state of the

labor market has to be considered before a meaningful evaluation of the double dividend hypothesis can be done.

Some studies about the employment effects of environmental or climate policies disregard economic feedback effects and mainly just determine if a number of jobs have directly been created in a particular (environmentally related) sector. More comprehensive studies employ some kind of theoretical model that maps the economic reality into a simplified system. Different models make different assumptions about the labor markets and the economic mechanisms at work, for example, just with respect to the processes at the labor market, one could employ a wage bargaining model, an efficiency wage model or a job-matching model. OECD roughly groups the economic models into a) econometric models that are usually demand driven and allow for disequilibrium markets b) general equilibrium models which are based on simultaneous equilibria on all involved markets and c) partial equilibrium models. Most models assume exogenous technical change and exogenous and fixed preferences. Due to the variety of assumptions that may still be altered, different results occur. However, the OECD can identify some general tendencies regarding the potential occurrence of a double dividend (OECD (2004)): " A strong double dividend cannot occur if the existing tax structure is revenue-optimal. If, as is likely in practice, the existing tax structure is not revenue-optimal, a strong double dividend will occur if the environmental tax reform moves the tax structure in the direction of revenue-optimality. In a situation with involuntary unemployment, employment will only increase if the use of environmental taxes to partially replace existing taxes results in an increased demand for labor. If the labor market is in equilibrium, additional employment could only be caused by increasing labor supply."

On a general level, no necessary or sufficient conditions can be found for when an increase in environmentally related taxes combined with a reduction in e.g. payroll taxes will increase employment - in addition to the first dividend stemming from an improvement in the environmental situation. Based on the study by Heady, Markandya, Blyth, Collingwood, and Taylor (2000), OECD (2004) identifies the following factors that make the occurrence of a double dividend it more likely. When there is involuntary unemployment, the prospects of increased employment are higher if:

1. The environmental tax can be passed on to factors that are inelastically supplied and relatively under-taxed.
2. Non-working households are large enough in numbers, and are significant as consumers of goods produced with the environmentally intensive inputs that are taxed.
3. Through international market power, the environmental tax can raise the price of goods produced with a relatively intensive use of the taxed environmental input.
4. Capital is relatively immobile internationally. In this case it can absorb some of the environmental tax and less of the tax burden falls on factors such as labor.
5. The elasticity of substitution between the environmental input and labor is greater the elasticity of substitution between energy and capital.
6. The real wage rises little when unemployment falls, so that the reduction in the taxes on labor are not offset by wage rises.

When there is only voluntary unemployment, conclusions (1) to (4) still hold, but conclusions (5) and (6) are replaced by: The environmental tax is levied on goods that are more complementary to leisure in consumption than the goods whose taxes are reduced.

Significant research on climate change in general has been done by the MIT Joint Program on the Science and Policy of Global Change. The Program integrates multidisciplinary expertise from the Center for Energy and Environmental Policy Research and the Center for Global Change Science and collaborates with other major research groups within and outside MIT (see <http://globalchange.mit.edu/index.html>). At the heart of the Joint Program's work lies the MIT Integrated Global System Model (IGSM). This comprehensive tool analyzes interactions among humans and the climate system. The Emissions Prediction and Policy Analysis (EPPA) model is a component of the IGSM (see Babiker, Reilly, Mayer, Eckaus, Wing, and Hyman, 2001) which is also designed to evaluate the economic impacts of policies designed to limit GHG emissions. EPPA belongs to a class of economic simulation models known as computable general equilibrium (CGE) models. Babiker and Eckaus (2006) use the EPPA model to theoretically study the unemployment effects of restrictions on greenhouse gas emissions. A variety of research papers focussing on different economic aspects of the climate change have been produced by the MIT Joint Program (see <http://globalchange.mit.edu/pubs/reports.php>).

Babiker and Eckaus (2006) allow for labor market rigidities, for example limited mobility of labor among sectors, and thus include scenarios in which involuntary unemployment occurs. The authors simulate three different scenarios for the following labor market environments: (1) mobile labor and flexible wages, (2) sector specific labor, but flexible wages (3) mobile labor, but rigid wages, (4) sector specific labor and rigid wages. The three climate policy scenarios are: (1) no greenhouse gas policy restrictions (reference solution), (2) Kyoto-like emissions restrictions imposed, without any offsetting policies;(3) Kyoto emissions restrictions, but with labor subsidies to offset the unemployment and economically depressing effects of those restrictions. These cases are similar to the first and second case in our paper (carbon tax and carbon tax with wage subsidies).

Babiker and Eckaus (2006) are hesitant to give exact measures of the effects due to the limits of data and the EPPA model. However, they find similar but not identical empirical results as we do. Their analysis indicates that "there would be a real, direct depressing effect from the imposition of emissions restrictions." The employment effects are expected to be only small but negative. The negative effects are mainly caused by a reduction in GDP growth under the implemented climate policies. Thus, in their modeling framework they cannot find support for the double dividend hypothesis. They recommend that other policy measures, for example wage subsidies, be implemented to mitigate negative employment effects of climate policies.

## 7 Conclusion

Given the great urgency to implement effective climate policies to reduce global warming a dynamic model with structural change and, related to that, concrete policy proposals of CO<sub>2</sub> emission have been developed in this paper. We consider three types of policies: 1) changing households' preferences, 2) imposing carbon tax and subsidizing labor (or reducing overhead cost for labor),

and 3) imposing carbon tax and subsidizing the development of less carbon intensive products. We study the dynamics of the growth model with those policies. In the empirical part of the paper the effects of those policy measures on structural change of output and employment are explored. In order to do so the carbon intensities of industries for the German economy are computed and the empirical effects of policy measures studied. We do not empirically estimate the the role of the change of preferences. Only indirect empirical evidence is cited. The actual empirical evaluation of the carbon tax policies is undertaken by a new kind of a VAR. As the intuition might suggest, the least favorable outcome is obtained when only a carbon tax rate is imposed on carbon intensive industries and the revenue not used for other purposes such as reducing other tax rates, subsidizing wage or payroll tax or the development of other (less carbon intensive) products. Since our proposed VAR allows us to permit budgetary neutrality we study the cases when the revenue is used for other purposes. The empirical results show that in particular the third policy measure where carbon taxes are used to subsidize the development of other products has the greatest net gains in terms of output and employment.

## 8 Appendices

### Appendix 1: Stability Analysis of the Base Line Model

We may summarize our model's dynamics as

$$\begin{aligned} \dot{l}_t &= \left[ \frac{B_K F_1(k_t, 1) - \delta - \rho}{\sigma} - g_t \right] l_t, \\ \dot{h}_t &= \left[ \frac{B_K F_1(k_t, 1) - \delta - \rho}{\sigma} - g_t \right] h_t, \end{aligned}$$

and

$$\dot{k}_t = B_K F(k_t, 1) - P_H h_t - P_L l_t - (g_t + \delta) k_t.$$

Define the Jacobian matrix of our  $3 \times 3$  dynamic system as

$$\begin{aligned} J &= \begin{bmatrix} \frac{\partial \dot{l}_t}{\partial l_t} & \frac{\partial \dot{l}_t}{\partial h_t} & \frac{\partial \dot{l}_t}{\partial k_t} \\ \frac{\partial \dot{h}_t}{\partial l_t} & \frac{\partial \dot{h}_t}{\partial h_t} & \frac{\partial \dot{h}_t}{\partial k_t} \\ \frac{\partial \dot{k}_t}{\partial l_t} & \frac{\partial \dot{k}_t}{\partial h_t} & \frac{\partial \dot{k}_t}{\partial k_t} \end{bmatrix} \\ &= \begin{bmatrix} \frac{B_K F_1(k_t, 1) - \delta - \rho}{\sigma} - g_t & 0 & \frac{1}{\sigma} B_K F_{11}(k_t, 1) l_t \\ 0 & \frac{B_K F_1(k_t, 1) - \delta - \rho}{\sigma} - g_t & \frac{1}{\sigma} B_K F_{11}(k_t, 1) h_t \\ -P_L & -P_H & B_K F_1(k^*, 1) - (g + \delta) \end{bmatrix}. \end{aligned}$$

Denote  $J$  evaluated at the steady state where  $l_t = l^*$ ,  $h_t = h^*$ ,  $k_t = k^*$ ,  $g_t = g$ , and  $B_K F_1(k_t, 1) = \rho + \sigma g + \delta$  by  $J^*$ . Then the associated characteristic equation is

$$\begin{aligned} \det(J^* - \lambda I) &= \begin{vmatrix} -\lambda & 0 & \frac{1}{\sigma} B_K F_{11}(k^*, 1) l^* \\ 0 & -\lambda & \frac{1}{\sigma} B_K F_{11}(k^*, 1) h^* \\ -P_L & -P_H & B_K F_1(k^*, 1) - (g + \delta) - \lambda \end{vmatrix} \\ &= -\lambda \left[ \lambda^2 - \{B_K F_1(k^*, 1) - (g + \delta)\} \lambda + \frac{1}{\sigma} F_{11}(k^*, 1) (P_H B_K h^* + P_L B_K l^*) \right] \end{aligned}$$

where  $\lambda$  is the eigenvalue of  $J$ .

Thus the eigenvalues are

$$\lambda_1 = 0 \text{ and } \lambda_{2,3} = \frac{B_K F_1(k^*, 1) - (g + \delta) \pm \sqrt{\Delta}}{2},$$

where

$$\Delta \equiv \{B_K F_1(k^*, 1) - (g + \delta)\}^2 - \frac{4}{\sigma} F_{11}(k^*, 1) (P_H B_K h^* + P_L B_K l^*) > 0.$$

Therefore, we have a zero eigenvalue, a real positive eigenvalue, and a real negative eigenvalue.

## Appendix 2: Changes of Demand Structure

In its annual environmental economic report 2002 ("Umweltökonomische Gesamtrechnungen 2002")<sup>10</sup> 2002, the German Federal Statistical Office ("Statistisches Bundesamt") specifically analyzed the contributions of the above five factors on total reduction of German  $CO_2$  emissions over the years 1991 to 2000 (see Statistisches-Bundesamt (2002)). It was found that there exist considerable differences: While total emissions declined by 92,3 million tons over the whole period,  $CO_2$  emissions caused by volume of final demand - not surprisingly - *increased* by 144,9 mill. tons, while the emissions due to the other factors all fell:  $CO_2$  intensity of the energy sources (-58.9 mill. tons), energy intensity of the production (-89,8 mill. tons), structure of intermediate goods (-40.4 mill. tons), structure of final demand (-48 mill. tons). For the period 1993 - 2000, the reduction of  $CO_2$  emissions due to changes in the final demand structure (-49.9 mill. tons) and the structure of intermediate goods (-37.8 mill. tons) were the second and third largest reductions in  $CO_2$  emissions. Only the decrease in energy intensity (-62 mill. tons) had a larger effect on total  $CO_2$  reductions. The change of  $CO_2$  intensity of energy sources contributed to a decline of 27.3 million tons. The volume effect of final demand was again expansive with an amount of +146.4 million tons. In other words, the two structural effects were 83% and 38% stronger than the effect of switching to less carbon intensive energy sources ( $CO_2$  intensity of the energy sources).

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<sup>10</sup>The "Umweltökonomische Gesamtrechnungen" are supplementary reports to Germany's national income and product accounts

### Appendix 3: Country Specific Estimates of the VAR

The sample statistics and parameter estimates of the nine countries are as follows:

#### Germany:

Table 2: Summary Statistics (Germany)

	$out_{hi,t}$	$out_{lo,t}$	$emp_{hi,t}$	$emp_{lo,t}$
Mean	2.17	3.07	-0.24	0.42
$out_{hi,t}$	3.99	2.31	0.91	1.48
$out_{lo,t}$	0.74	2.42	0.71	1.19
$emp_{hi,t}$	0.44	0.45	1.03	0.86
$emp_{lo,t}$	0.67	0.69	0.77	1.21

Bottom panel: Variances (diagonal elements), covariances (above-diagonal elements), and correlations (below-diagonal elements)

$$\hat{c}_{GER} = \begin{bmatrix} 0.81 \\ 1.19 \\ -0.61 \\ -0.86 \end{bmatrix}, \hat{A}_{GER} = \begin{bmatrix} -0.20 & 0.69 & -0.24 & -0.48 \\ -0.19 & 0.76 & -0.38 & -0.12 \\ -0.20 & 0.36 & 0.29 & -0.04 \\ -0.22 & 0.66 & 0.25 & -0.26 \end{bmatrix}, \hat{\Sigma}_{GER} = \begin{bmatrix} 3.03 & 1.56 & 0.30 & 0.92 \\ 1.56 & 1.63 & 0.25 & 0.59 \\ 0.30 & 0.25 & 0.14 & 0.23 \\ 0.92 & 0.59 & 0.23 & 0.54 \end{bmatrix}.$$

With the eigenvalues of  $\hat{A}_{GER}$  being  $0.4698 \pm 0.2444i$  and  $-0.1739 \pm 0.1149i$  and the moduli being 0.5296 and 0.2085, the estimated system is stable.

#### Australia:

#### France:

#### Hungary:

Table 3: Summary Statistics (Australia)

	$out_{hi,t}$	$out_{lo,t}$	$emp_{hi,t}$	$emp_{lo,t}$
Mean	5.60	6.54	1.43	1.53
$out_{hi,t}$	7.00	3.70	2.65	3.80
$out_{lo,t}$	0.51	7.38	0.53	3.04
$emp_{hi,t}$	0.74	0.14	1.80	1.61
$emp_{lo,t}$	0.45	0.35	0.38	9.90

Bottom panel: Variances (diagonal elements), covariances (above-diagonal elements), and correlations (below-diagonal elements)

Table 4: Summary Statistics (France)

	$out_{hi,t}$	$out_{lo,t}$	$emp_{hi,t}$	$emp_{lo,t}$
Mean	5.44	6.14	0.29	0.72
$out_{hi,t}$	16.44	12.74	-0.09	-0.03
$out_{lo,t}$	0.88	12.65	0.25	1.15
$emp_{hi,t}$	-0.03	0.12	0.34	0.60
$emp_{lo,t}$	0.01	0.23	0.75	1.87

Bottom panel: Variances (diagonal elements), covariances (above-diagonal elements), and correlations (below-diagonal elements)

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Table 5: Summary Statistics (Hungary)

	$out_{hi,t}$	$out_{lo,t}$	$emp_{hi,t}$	$emp_{lo,t}$
Mean	13.06	17.63	-0.97	0.52
$out_{hi,t}$	35.61	37.27	-3.83	-0.91
$out_{lo,t}$	0.84	54.85	-3.26	1.07
$emp_{hi,t}$	-0.22	-0.15	7.87	4.02
$emp_{lo,t}$	-0.05	0.05	0.51	7.73

Bottom panel: Variances (diagonal elements), covariances (above-diagonal elements), and correlations (below-diagonal elements)

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