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**Volkswirtschaftliche
Diskussionsbeiträge**



Emission Tax Revenues in a Growing Economy

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Discussion Paper No. 61-97

**UNIVERSITÄT GESAMTHOCHSCHULE SIEGEN
FACHBEREICH WIRTSCHAFTSWISSENSCHAFTEN**

EMISSION TAX REVENUES IN A GROWING ECONOMY

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Abstract:

This paper focuses on how emission tax revenues change relative to GNP, when a fixed environmental standard is implemented by an emission tax and when waste abatement, technical and structural change and capital accumulation is accounted for. One- and two-sector growth models are analyzed allowing for demand substitution and sectoral differences in emission intensities and elasticities of technical substitution. It turns out that the more difficult it is to reduce the emission of pollutants either by abatement or by shifting the demand towards low-pollution goods the more likely emission taxes are reliable long-term sources of tax revenues.

Key words: Environmental tax reform, emission tax revenues, economic growth

JEL-Classification: E13, H23, Q28

1. Introduction

The recommendation of emission taxes as environmental policy instruments is based on their capacity of efficiently internalizing environmental externalities. Expressed in public finance language, the focus is on these taxes' incidence, since it is the tax base eroding effect of increasing tax rates, which improves environmental quality. Therefore, in contrast to most other taxes the principal *raison d'être* of emission taxes is not their capacity of raising tax revenue. One could even argue that emission taxes serve their purpose the better the smaller is their revenue.

It is appropriate, therefore, that early studies on emission taxes did not pay much attention to the pertaining tax revenues. As far as general equilibrium analysis was applied, tax revenues were normally assumed to be recycled to consumers as lump-sum transfers.¹ However, in recent years the interest in emission tax revenues grew, when in practical policy as well as in the professional discussion the attention grew for environmental tax reforms whose aim is to levy (or raise the rate of) an emission tax and use the resultant additional emission tax receipts to reduce the rate of other distortionary taxes keeping total tax revenue constant. Emission tax revenues are important for the successful implementation of such a tax reform for two reasons. Firstly and quite obviously a revenue-neutral replacement of conventional taxes by environmental taxes presupposes that increasing emission tax rates generate incremental tax revenues (Laffer efficiency²) which is, of course, the usual assumption made in studies on environmental tax reforms (e. g. Bovenberg and de Mooij (1994)).

The second reason, perhaps not so obvious but at least as crucial for the assessment of environmental tax reforms, is that emission taxes should be reliable with respect to their long-run capacity of earning tax revenue in an economy subject to growth and structural change. Leaving aside the Laffer efficiency argument the present paper aims at investigating an emission tax's long-term performance regarding its contribution to fiscal revenue. We take it as a stylized fact that governments seek to keep roughly constant over time the ratio of total tax revenue to GNP. It follows then that, unless emission tax revenues grow at about the same rate as GNP, these taxes are disadvantageous from the fiscal point of view. For politicians, it is probably particularly awkward when the growth of (emission) tax revenue falls short of GNP growth. This is what some public finance economists expect to happen, and why they reject the concept of environmental tax reform as, e. g. Hansmeyer and Schneider (1990, p. 64n) and Linscheidt and Truger (1995, p. 96 - 107).

At first sight it appears natural to address this issue of tax revenue stability by investigating the long-term development of these revenues under the assumption of a time invariant emission tax rate. But such an approach would be inappropriate, in our view, because it would leave to

¹ There was some discussion about the recommendation to spend tax revenues on environmental subsidies or public investments to clean up the environment. But the theory-oriented environmental economist insisted, correctly so, that earmarking the receipt of emission taxes is no valid argument in favor of these taxes except for political economy reasons, perhaps.

² In the context of general equilibrium analysis, the magnitude and the sign of the tax rate elasticity of emission tax revenues is of considerable importance. However, this issue is not the focus of the present paper.

(arbitrary) endogenous changes over time the flow of total emissions of pollutants and hence environmental quality. We contend that the primary goal of emission taxes remains to fight pollution problems while the fiscal purpose of revenue raising is a side effect (attracting increasing attention, though). In this paper, we therefore take as the point of departure an environmental policy that implements an aggregate time-invariant emission standard at each point in time by means of an emission tax. The issue then is how the resultant emission tax revenues change over time relative to GNP.³

We know from conventional growth theory (e. g. Krelle, Gabisch and Burgermeister (1972), Ramanathan (1982)) that if exogenous growth of the labor force is excluded, as assumed in the present paper, continuous growth of GNP is not feasible without technical change. We therefore introduce different types of technical change (capital-augmenting, 'emission-saving' and Hicks neutral) to characterize possible growth paths of the economy. Special emphasis is also placed on the role of waste abatement technologies and on the role of demand substitution in an economy with two consumption goods that are assumed to differ with respect to the emission intensity in their production.

Sector 2 investigates the one-sector growth model emphasizing the production-cum-abatement technology and technical change. It turns out that the degree to which marginal abatement costs increase determines either exclusively (section 2.2) or essentially (section 2.3) whether the emission tax share of GNP rises or shrinks. Section 3 develops a two-sector growth model where an industrial good is used both for capital formation and consumption and where the second consumption good, called services, is less emission intensive in its production than the industrial good. Not surprisingly, in this model the development in time of the emission tax share depends on a richer set of determinants and on special constellations of their interaction, because economic growth is accompanied by structural change.

2. The one-sector economy

2.1 Capital accumulation, technical change and optimal growth

Consider an economy in which the only (aggregate) *consumption good* is produced according to the linear homogeneous production function $Y : D_y \rightarrow \mathfrak{R}_+$ with domain

$D_y := \{(e, k) \in \mathfrak{R}_+^2 \mid k \geq \underline{x}e, \underline{x} > 0 \text{ and } \text{const.}\}$. We interpret

$$y = Y \underset{\substack{(+)}{e}, \substack{(+)}{k}}{(e, k)} \quad (1')$$

as the quantity of good Y produced and k as the *capital input*. In (1') the letter ' e ' stands for *emission* of pollutants. From the producer's viewpoint the emission of pollutants amounts to making use of nature's *services* of assimilating pollutants which are generated in the process of producing good Y and then discharged into the environment.

Following the tradition of growth theory capital formation will be treated as endogenous (to be specified below). The aggregate amount of pollutants allowed to be emitted into the environment is limited at or below nature's capacity to regenerate. For simplicity this politically

³ Observe that keeping emissions constant over time in an economy subject to growth and structural change may require to adjust the emission tax rate upward or downward. Such changes are caused by environmental policy consideration, however, rather than by the fiscal purpose of revenue raising.

determined *emission standard*, \bar{e}_t , is assumed to be time invariant: $\bar{e}_t = \bar{e}$ for all t . Since $Y_e(k, \bar{e}) > 0$ for all $(k, \bar{e}) \in D_y$, we safely set $e = \bar{e}$ in the subsequent analysis (rather than $e \leq \bar{e}$). The possibility of *technical change* is accounted for because the focus of our analysis is on the long term. Using the concept of factor augmentation (Ramanathan (1982)) we redefine (1') to read

$$y = Y(\alpha e, \kappa k), \quad (1)$$

where κ and α are efficiency terms which are non-decreasing over time and whose growth rates are $\hat{\kappa} \geq 0$ and $\hat{\alpha} \geq 0$, respectively. Observe that $\hat{\alpha} \geq 0$ is well compatible with the constraint $e_t = \bar{e}$ for all t , since the efficiency term $\alpha > 1$ only means that the technical change works *as if* the politically determined emission standard \bar{e} had been relaxed to $\alpha \bar{e} > \bar{e}$. In fact, the case $\kappa \equiv 1$ and $\hat{\alpha} > 0$ represents '*emission saving*' technical change. A satisfactory explanation of economic growth would require to endogenize the determinants of $\hat{\kappa}$ and $\hat{\alpha}$ (e.g. learning by doing). But since our focus is on how emission tax revenues respond to technical change (of some variety) we do not gain additional insight by explaining why technical change takes place. To avoid unnecessary complexity of modelling, we therefore consider $\hat{\alpha}$ and $\hat{\kappa}$, the growth rates of the efficiency terms, as exogenous. For further simplification, we set $\beta \equiv 1$ whenever $\hat{\beta} = 0$ (for $\beta = \alpha, \kappa$).

Turning to the demand side of our simple growth model we denote by c the amount of good Y consumed and introduce the instantaneous utility function

$$u = U \left(\underset{(+)}{c}, \underset{(-)}{e} \right) \quad \text{with} \quad \frac{u U_{cc}}{U_c} =: \eta_{uc} < 0 \quad \text{and constant.}$$

$U_e < 0$ reflects the marginal damage caused by the emission of pollutants. The model could be expanded to consider the accumulation of pollutants and the detrimental effects of stock pollution in addition to those of flow pollution (e). But we refrain from this complication for convenience of exposition.

The share of production exceeding consumption (c) and capital depreciation (δk) is used for capital investment:

$$\dot{k} = Y(\alpha \bar{e}, \kappa k) - c - \delta k. \quad (2')$$

Linear homogeneity of Y implies that there is a function $Q: \mathfrak{R} \rightarrow \mathfrak{R}$ satisfying

$$Y(\alpha \bar{e}, \kappa k) = \alpha \bar{e} Q(x) \quad \text{with} \quad x := \frac{\kappa k}{\alpha \bar{e}} \quad \text{and} \quad Q(x) = \frac{y}{\alpha \bar{e}} =: q.$$

As a consequence, (2') can be rewritten as

$$\dot{k} = \alpha \bar{e} Q(x) - c - \delta \frac{\alpha \bar{e} x}{\kappa} \quad \text{or} \quad x \dot{k} = \kappa Q(x) - \frac{\kappa c}{\alpha \bar{e}} - \delta x. \quad (2'')$$

Moreover, differentiating x with respect to time yields $\dot{x} = x(\hat{k} - \hat{\alpha} + \hat{\kappa})$ which, after consideration of (2''), reads

$$\dot{x} = x(\hat{\kappa} - \hat{\alpha} - \delta) + \kappa Q(x) - \frac{\kappa c}{\alpha \bar{e}}. \quad (2)$$

Having thus completed the description of the model we now turn to investigating the optimal time path of x and c by solving:

$$\text{Maximize } \int_0^{\infty} e^{-\rho t} U(c, \bar{e}) dt \quad (\rho > 0 \text{ and constant}) \quad \text{subject to (2)}. \quad (3)$$

This optimal control problem essentially coincides with the standard neoclassical growth model except for the reinterpretation of labor as emission of pollutants. The properties of the optimal time path are derived in the appendix A by standard arguments. It is shown, in particular, that the solution of (3) is characterized by

$$\hat{c} = \frac{\rho + \delta - \kappa Q_x(x)}{\eta_{uc}} = - \frac{\kappa Q_x(x) - \rho - \delta}{\eta_{uc}}. \quad (4)$$

This differential equation is applied to answer the question how the capital intensity (in efficiency units) changes over time which, in turn, will prove to be decisive for the change of the emission tax share of GNP over time. The relevant results of appendix A are summarized in

Proposition 1: *The optimal time path is characterized as follows:*

- (a) *If $(\hat{\alpha} = 0, \hat{\kappa} > 0)$ or $(\hat{\alpha} = \hat{\kappa} > 0)$ then \hat{x} tends to be positive in the long run.*
- (b) *If $(\hat{\alpha} > 0, \hat{\kappa} = 0)$ or $(\hat{\alpha} = \hat{\kappa} = 0)$ then x eventually attains the steady state value $x^* = Q_x^{-1}(\rho + \delta)$ and this state is approached⁴ with $\hat{x} > 0$ if x_0 , the initial value of x , satisfies $x_0 < x^*$.*

2.2 Determinants of the emission tax share in the process of growth

As is well known, the optimal intertemporal allocation can be decentralized by perfectly competitive markets for capital and the consumption good.⁵ If emissions were sold via marketable permits we would have an additional perfectly competitive market. An equivalent allocation procedure which we refer to, in what follows, is that an emission tax is levied at such a rate that at any point in time the predetermined emission standard is met. In other words, we employ the environmental tax-and-standard approach as suggested by Baumol and Oates (1971) to a growing economy. The emission tax rate which does that job is

$$\tau := \tau_e \alpha = (q - x Q_x) \alpha, \quad \text{where } \tau := Y_e \Big|_{e=\bar{e}} = \frac{\partial Y}{\partial e} \Big|_{e=\bar{e}} \quad \text{and} \quad \tau_e := Y_{\bar{e}} := \frac{\partial Y}{\partial (\alpha e)} \Big|_{e=\bar{e}}$$

⁴ If $x_0 > x^*$, the steady state is approached with $\hat{x} < 0$.

⁵ Traditionally, the positive theory of economic growth relied on the assumption that the marginal saving rate is constant. Here as well as in the next section we decentralize the optimal time path without any presumption regarding the saving rate.

Clearly, the rate τ is a charge per unit of emissions in terms of the industrial good. The relevant *emission tax revenue* is $\tau \bar{e}$, and the ratio of the emission tax revenue to GNP is $\theta := \tau \bar{e}/y$ which we refer to as the *emission tax share*. The ratio $\tau \bar{e}/y$ can be rewritten by making use of the assumption that Y is linear homogeneous. Observe that

$$\omega := \frac{q - xQ_x}{Q_x} = \frac{\tau_e}{Q_x}$$

is the tax rate per efficiency unit of emissions in terms of capital. Consider also that $q = (q - xQ_x) + xQ_x$ (Euler's equation) implies $q = Q_x(\omega + x)$. Hence

$$\theta = \frac{\omega}{\omega + x}. \quad (5)$$

Taking the derivative of (5) with respect to time yields

$$\frac{\hat{\theta}}{1 - \theta} = \hat{\omega} - \hat{x} = \frac{1 - \sigma}{\sigma} \hat{x}, \quad (6)$$

where $\sigma := \frac{d\left(\frac{k}{e}\right)}{\frac{k}{e}} \cdot \frac{\frac{Y_e}{Y_k}}{d\left(\frac{Y_e}{Y_k}\right)} = \frac{\hat{x}}{\hat{\omega}} \geq 0$ is the *elasticity of technical substitution*.

When (6) is combined with proposition 1 we obtain

Proposition 2: *The emission tax share grows /is constant / shrinks, if and only if σ is smaller than / equal to / greater than unity. This observation holds*

- (a) *indefinitively through time, if the technical change is capital augmenting or Hicks neutral;*
- (b) *until a steady state is reached, if technical change is 'emission saving' or completely absent and if, in addition⁶, $x_0 < Q_x^{-1}(\rho + \delta)$.*

According to proposition 2 the long-run revenue-generating capacity of emission taxes is determined by both the type of technical change and the elasticity of substitution, σ . The latter is closely related to the waste abatement technology implicitly incorporated in the production function Y . To clarify this relationship suppose for a moment that (i) both the consumption good Y and a pollutant are produced in strict proportion to capital input and that (ii) there is an abatement technology with non-increasing returns to scale which 'neutralizes' the pollutant using capital input. We now demonstrate with the help of figure 1 that these production technologies (i) and (ii) can be represented by a production function with properties similar to those assumed for function Y in (1) and we also show that greater values of σ correspond to a reduction in the increase of marginal abatement costs.⁷

Suppose the straight line OA in figure 1 represents a linear production process without abatement activity where the good Y and the pollutant are produced in fixed proportion. Let

⁶ In case of $x_0 > Q_x^{-1}(\rho + \delta)$ the reverse statement holds.

⁷ For more details, see Pethig (1979, p. 22 - 26)

point P_1 be the actual production point satisfying $y_1 = Y(e_1, k_1)$. The production isoquant for $y = y_1$ passes through P_1 and extends to the northwest of point P_1 , say like the line P_1B in figure 1.

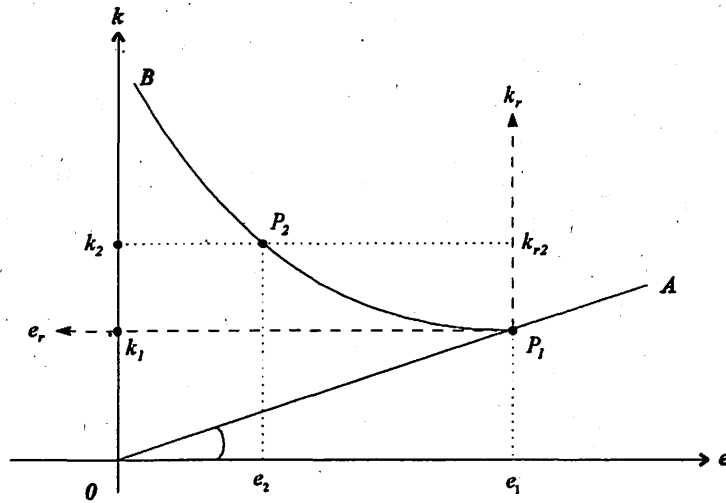


Figure 1: Production cum waste abatement

If we move from P_1 to P_2 along this isoquant we reduce the emission of pollutants from e_1 to e_2 by using additional capital $k_2 - k_1 > 0$. Since the level of output is the same in P_1 and P_2 , production in P_2 can be interpreted as first producing y_1 in P_1 with a linear technology without abatement and then abating the waste generated, e_1 , to the level $e_2 < e_1$. The implicit waste abatement technology can be illustrated in figure 1 by choosing P_1 as the origin of an auxiliary coordinate system (drawn by dashed lines) in which the line P_1B shows how much output "reduced emissions" (e_r) is produced by any given capital input (k_r). In fact, reading this coordinate system from the e_r -axis to the k_r -axis the line P_1B gives us a strictly increasing abatement cost curve where the cost is measured in terms of capital. The greater the curvature of this curve, the greater is the curvature of the y -isoquant which, in turn, increases with decreasing elasticity of substitution, as claimed above.

In view of this illustration, the message of proposition 2 is straightforward: In a growing economy ($\hat{x} > 0$) the revenue-earning capacity (relative to GNP) of the emission tax is the greater the greater is the increase of marginal abatement costs in terms of capital, i.e. the less efficient are, at the margin, man-made abatement efforts as compared to nature's assimilative services. The type of technical change determines whether changes in the emission tax share are permanent (and in the same direction) or tend to zero when a steady state is approached.

2.3 Fossil fuel and energy taxation in a small open economy

Leaving the formal structure of the model (almost) unchanged we now consider the variable e in (1') as *energy input*, assuming that fossil fuel is assumed to be the only source of energy. Total fossil fuel consumption is restricted to \bar{e} , and since CO_2 is generated in fixed proportion in the process of burning fossil fuel, \bar{e} is an emission standard at the same time. So far, the previous model has only been reinterpreted. But now an important substantive difference comes in, because energy is not a costless factor of production. In line with the real situation of many (small) countries we assume that all energy is imported at an *exogenous world market price*, p_e . Hence at each point in time the import bill is $p_e \bar{e}$ which, in turn, is paid for by ex-

porting the quantity $y_e = p_e \bar{e}$ of good Y. This export is taken care of in the formal model by modifying the equation (2') to

$$\dot{k} = Y(\alpha \bar{e}, \kappa k) - p_e \bar{e} - c - \delta k. \quad (2''')$$

Maximizing the present value of utility subject to (2''') does not change the dynamics of growth in an essential way provided that $p_e \bar{e}$ is sufficiently small.

Energy input is taxed at the rate t_e so that the *energy tax share* is $\beta := t_e \bar{e} / y$. The after tax value of energy as a share of GNP is⁸

$$\theta_e := \frac{(p_e + t_e) \bar{e}}{y} = \frac{\omega_e}{\omega_e + x} \quad (7)$$

$$\text{where } \omega_e := \frac{(p_e + t_e) \bar{e}}{Q_x} = \frac{q - x Q_x}{Q_x}.$$

Differentiation of (7) with respect to time yields, after some rearrangement of terms,

$$(1 - \gamma) \hat{p}_e + \gamma \hat{t}_e - \hat{y} = \frac{1 - \sigma}{\sigma} \hat{x} \quad (8)$$

where $\gamma := \beta / \theta_e$. Observe that $\hat{y} = \hat{\alpha} + (1 - \theta_e) \hat{x}$ (using $y = \alpha \bar{e} Q(x)$ and $q = (\omega_e + x) Q_x$) and $\hat{\beta} = \hat{t}_e - \hat{y}$. When these equations are considered in (8') one obtains, after some rearrangement of terms,

$$\gamma \hat{\beta} = (1 - \beta)(\hat{\alpha} - \hat{p}_e) + \frac{1 - \rho \sigma}{\sigma} \hat{x} \quad (9)$$

with $\rho := (1 - \gamma)(1 - \theta_e) = \frac{p_e \theta_e + t_e}{p_e + t_e} \in]0, 1[$. The basic message of (9) is summarized in

Proposition 3: *Suppose, an energy tax is levied in a growing small open economy with a time-invariant CO₂-emission standard.*

- (a) *Let $\hat{p}_e = \hat{\alpha} \geq 0$ and $\hat{x} > 0$. Then the energy tax share grows/ is constant/ shrinks, if and only if $\rho \sigma$ is smaller than/ equal to/ greater than unity.*
- (b) *For any given ρ, σ and $\hat{x} > 0$ the change of the energy tax share is increased/ constant/ decreased, if and only if $\hat{\alpha}$ is greater than/ equal to/ smaller than \hat{p}_e .*

Observe that the time paths of energy-saving technical change, α , and of the world energy price, p_e , are exogenous to our model. It is plausible to expect that the world energy price (in terms of the consumption good) will increase in the medium and long term ($\hat{p}_e > 0$). But $\hat{\alpha}$ is difficult to forecast. Therefore the sign of the difference $\hat{\alpha} - \hat{p}_e$ and its impact on $\hat{\beta}$ (proposition 3b) is empirically hard to determine. In contrast, the constellation of proposition 3a shows that if the effects of \hat{p}_e and $\hat{\alpha}$ on $\hat{\beta}$ are assumed to neutralize each other the pro-

⁸ In terms of the formal model, θ_e and ω_e are identical to θ and ω in the model of section 2.2.

spects for $\hat{\beta} > 0$ are more favorable than in the model of section 2.2 because $\rho \in]0, 1[$. Moreover, it is a well established empirical fact that the elasticity of substituting capital and energy in production, σ , is less than unity. Hence $\rho\sigma < \sigma < 1$ and therefore $\hat{\beta} > 0$ under the constellation of proposition 3a. We are led to conclude, therefore, that $\hat{\beta} > 0$ can be expected as a response to $\hat{x} > 0$ provided that \hat{p}_e does not exceed $\hat{\alpha}$ by too much.

3. The two-sector economy

3.1 Capital accumulation, technical change and growth

The one-sector model of the previous section allowed us to investigate the impact of abatement and technical change on the development of the emission tax share over time. Additional determinants emerge in economies with more than one consumption good, because these goods will differ in general with respect to their emission intensities in production, with respect to their elasticities of technical substitution, and they may also be complements or substitutes in consumption. To investigate these effects we now consider a *two-sector model* where one sector is interpreted as the (low-pollution) *service sector*, indexed by s , and where the other sector is called the (pollution intensive) *industry*. The output of industry can be invested or consumed like the aggregate good in the one-sector economy of the previous section while services are used for consumption only.⁹ In formal terms we have

$$y_v = \alpha e_v Q^v(x_v) = \alpha \bar{e} \lambda_v Q^v(x_v) \quad v = i, s$$

where $x_v := \kappa k_v / \alpha e_v$ and $\lambda_v := e_v / \bar{e}$. For convenience of exposition, the efficiency terms κ and α are assumed to be the same across sectors. The resource constraints $e_i + e_s = \bar{e}$ and $k_i + k_s = k$ can be rewritten as

$$x := \frac{\kappa k}{\alpha \bar{e}} = \lambda_i x_i + \lambda_s x_s \quad \text{and} \quad \lambda_i + \lambda_s = 1. \quad (10)$$

Production and consumption of the industrial good satisfy the differential equation

$$\dot{k} := \alpha \bar{e} \lambda_i Q^i(x_i) - \delta k - c_i \quad \text{or} \quad \dot{x} := x(\hat{\kappa} - \hat{\alpha} - \delta) + \lambda_i \kappa Q^i(x_i) - \frac{\kappa c_i}{\alpha \bar{e}}. \quad (11)$$

Since by assumption services are for consumption only we write $y_s = c_s$. In this model, optimal growth results from solving:

$$\text{Maximize } \int_0^{\infty} e^{-\rho t} U(c_i, c_s, \bar{e}) dt \quad \text{subject to (11) and } c_s = y_s = \alpha \bar{e} \lambda_s Q^s(x_s). \quad (12)$$

As shown in appendix B the optimal time path is characterized by

$$\omega_i(x_i) = \omega_s(x_s), \quad (13)$$

⁹ A variety of two-sector growth models have been studied in the 1960s. See e. g. Ramanathan (1982) and the references given there (p. 294). However, the standard two-sector model of this literature assumes that the capital (or industrial) good is not used for consumption at all with the consequence that demand-induced structural change is excluded from the analysis in that model.

$$\hat{c}_i - \hat{c}_s = \frac{\sigma_c \omega Q_x^i Q_x^s}{q_i q_s \sigma_i} (x_i - x_s) \hat{x}_i = - \frac{\sigma_c \omega (x_s - x_i)}{\sigma_i (x_i + \omega)(x_s + \omega)} \hat{x}_i, \quad (14)$$

$$\hat{x} = \frac{\mu_i \sigma_i + \mu_s \sigma_s}{\sigma_i} \hat{x}_i - \frac{\mu_i (x_s - x_i)}{x_i} \hat{\lambda}_i, \quad (15)$$

where $\omega_\nu(x_\nu) := \frac{Q^\nu(x_\nu) - x_\nu Q_x^\nu(x_\nu)}{Q_x^\nu(x_\nu)}$ with $\nu = i, s$, where $\sigma_c := \frac{\hat{c}_i - \hat{c}_s}{d(U_s/U_i)/(U_s/U_i)} \geq 0$ is the elasticity of demand substitution (presupposing that the utility function U is homothetic), and where $\mu_\nu := \lambda_\nu x_\nu / x$ for $\nu = i, s$ with $\mu_i + \mu_s = 1$ owing to (10).

The concept of ω had already been employed in the one-sector model. Hence we identify $\omega_\nu(x_\nu)$ from (13) as the tax rate in sector ν per efficiency unit of emissions in terms of capital. The equation (13) requires to equalize these rates across sectors as a necessary optimality condition securing production efficiency. In formal analogy to the procedure in the standard model of international trade (e. g. Kemp 1969) we make precise the difference between both sectors regarding their environmental impact by introducing the assumption that $\omega_i(x_i) = \omega_s(x_s) = \omega$ implies $x_s > x_i$ for all $\omega > 0$. Its interpretation is straight forward: For any given emission tax rate ω , the same in both sectors (see (13)), the production in sector i is less capital intensive than in sector s . Denoting $1/x_\nu$ as 'emission intensity' it is equivalent to say that industry is relatively emission intensive in its production if $\omega_i(x_i) = \omega_s(x_s)$ implies $x_s > x_i$.

As in the previous section, we are mainly interested in the characteristics of the optimal time path of \hat{x} for alternative specifications of technical change. It is shown in the appendix B that the properties of the optimal time path of \hat{x} are very similar to those in the one-sector economy as summarized in proposition 1 except that the time paths towards steady states are less clear in the more complex two-sector model.

3.2 The response of the emission tax share to increasing capital intensity

For the purpose of the present paper it suffices to observe that a tendency towards increasing the economy's factor endowment ratio in efficiency terms, $\kappa k / \alpha \bar{e}$, either temporarily or permanently is a common feature of the specifications of technical change which have been considered here. In what follows we therefore investigate how the emission tax share changes when $\hat{x} > 0$. We choose the industrial good as numéraire and determine the emission tax share in the two-sector economy as

$$\theta = \frac{\tau \bar{e}}{y_i + p_s y_s} \quad (16')$$

with¹⁰ $\tau = \tau_e \alpha = (q_i - x_i Q_x^i) \alpha$. We aim at transforming (16') into an equivalent expression by a number of substitutions. Recall first that $\tau = \tau_e \alpha = \omega Q_x^i \alpha$ and $y_v = \alpha e_v q_v = \alpha \bar{e} \lambda_v q_v$.

Hence $\theta = \frac{\omega Q_x^i}{\lambda_i q_i + p_s \lambda_s q_s}$. Next we take into account $p_s = Q_x^i / Q_x^s$ and multiply both the denominator and the numerator by $1/Q_x^i$ to obtain $\theta = \frac{\omega}{\frac{\lambda_i q_i}{Q_x^i} + \frac{\lambda_s q_s}{Q_x^s}}$. Making use of (10)

and $q_v / Q_x^v = x_v + \omega$ (see above), θ becomes equal to

$$\theta = \frac{\omega}{x + \omega} \quad (16)$$

which is exactly the same term as equation (5) in section 2. Differentiation of (16) with respect to time yields $\hat{\theta} = (1 - \theta)(\hat{\omega} - \hat{x}) = (1 - \theta)\left(\frac{\hat{x}_i}{\sigma_i} - \hat{x}\right)$ after consideration of $\hat{\omega} \sigma_i = \hat{x}_i$. Substitution of \hat{x} from (15) leads to

$$\frac{\hat{\theta}}{1 - \theta} = \frac{1 - \bar{\sigma}}{\sigma_i} \hat{x}_i + \frac{\mu_i (x_s - x_i)}{x_i} \hat{\lambda}_i, \quad (17)$$

where $\bar{\sigma} := \mu_i \sigma_i + \mu_s \sigma_s = \frac{\lambda_i x_i \sigma_i + \lambda_s x_s \sigma_s}{x}$ and where $\mu_v := \lambda_v x_v / x$ (for $v = i, s$), $\mu_i + \mu_s = 1$. Note that $\bar{\sigma}$ is a weighted mean of the sectoral elasticities of technical substitution. The next step is to establish the relationship between $\hat{\lambda}_i$ and \hat{x}_i . To this end we introduce $s \in (0, 1)$, the marginal propensity to save in terms of the industrial good, and write $c_i = (1 - s)y_i$. Clearly, equilibrium in the commodity markets requires $(c_i / c_s) = [(1 - s)y_i / y_s]$ which yields $\hat{c}_i - \hat{c}_s = \hat{y}_i - \hat{y}_s$ under the simplifying assumption that $\hat{s} = 0$. We consider $y_v = \alpha \bar{e} Q^v(x_v)$ and $\sigma_s \hat{x}_i = \sigma_i \hat{x}_s$ to express the difference $\hat{y}_i - \hat{y}_s$ as

$$\hat{y}_i - \hat{y}_s = \frac{1}{\lambda_s} \hat{\lambda}_i + \frac{q_i(\omega + x_s)\sigma_i - q_s(\omega + x_i)\sigma_s}{\sigma_i(\omega + x_s)(\omega + x_i)} \hat{x}_i.$$

Equating this term with $\hat{c}_s - \hat{c}_i$ from (14) yields, after some rearrangements,

$$\frac{\mu_i (x_s - x_i)}{x_i} \hat{\lambda}_i = \frac{B}{\sigma_i} \hat{x}_i \quad (18)$$

where $B := m_1(\sigma_s - p_s \sigma_i) - m_0 \sigma_c$, $m_0 := \frac{\lambda_s \mu_i (x_s - x_i)^2 \omega}{x_i(\omega + x_s)(\omega + x_i)} > 0$, $m_1 := \frac{\lambda_s \mu_i q_s (x_s - x_i)}{x_i(\omega + x_s)} > 0$,

and $p_s := Q_x^i / Q_x^s$.

¹⁰ For convenience of notation, we use the same letter τ for the emission tax rate as in the one-sector model of the previous section.

The magnitude of B depends on $\sigma_c, \sigma_s, \sigma_i$ and on the assumption that the industry is more emission intensive in its production than the service sector ($x_s > x_i$). B is linear in all elasticities, but their impact on B differs (i) because B is decreasing in σ_i and σ_c , but increasing in σ_s and (ii) because all elasticities are non-negative.

The next step is to investigate how x_i responds to an increase in x . For that purpose we combine (17) and (15) yielding

$$\hat{x}_i = \frac{\sigma_i}{\bar{\sigma} - B} \hat{x} \quad (19)$$

which shows that the response of x_i to a change in x depends on all elasticities in a fairly complex way. The information contained in (19) is summarized as follows

Proposition 4: Let $\sigma_i, \sigma_s, \sigma_c \in]0, \infty[$ and $B \neq \bar{\sigma}$.

$$(a) \frac{\hat{x}_i}{\hat{x}} > 0;$$

$$(b) \frac{d(\hat{x}_i/\hat{x})}{d\sigma_c} = -\frac{m_o \sigma_i}{(\bar{\sigma} - B)^2} < 0;$$

$$(c) \frac{d(\hat{x}_i/\hat{x})}{d\sigma_s} = \frac{(m_1 - \mu_s) \sigma_i}{(\bar{\sigma} - B)^2} \underset{>}{\geq} 0 \Leftrightarrow m_1 \underset{>}{\geq} \mu_s;$$

$$(d) \frac{d(\hat{x}_i/\hat{x})}{d\sigma_i} = \frac{(\mu_s - m_1) \sigma_s + m_o \sigma_c}{(\bar{\sigma} - B)^2} \underset{>}{\geq} 0 \Leftrightarrow m_1 \underset{>}{\leq} \mu_s + \frac{m_o \sigma_c}{\sigma_s}$$

To prove proposition 4a observe first that (19) implies $(\hat{x}_i/\hat{x}) \underset{>}{\geq} 0$ iff $\bar{\sigma} \underset{>}{\geq} B$. To fix our ideas set $\hat{x} > 0$ and suppose first that $B > \bar{\sigma}$. Then $\hat{x}_i < 0$ and $\hat{x}_s < 0$. It is shown in the appendix B (equation (m)) that $\hat{p}_s \underset{>}{\geq} 0$ iff $\hat{x}_i \underset{>}{\leq} 0$. Hence $\hat{p}_s > 0$. Moreover, owing to the Rybcinski theorem we know that $\hat{x} > 0$, $x_s > x_i$ and $\hat{p}_s = 0$ implies $\hat{y}_i < 0$ and $\hat{y}_s > 0$. A fortiori, it is true that $\hat{y}_i < 0$ and $\hat{y}_s > 0$, if $\hat{p}_s > 0$. Therefore $\hat{y}_i - \hat{y}_s = \hat{c}_i - \hat{c}_s < 0$. But (14) requires $\hat{c}_i - \hat{c}_s > 0$ for $\hat{x}_i < 0$ (since $x_s > x_i$). From this contradiction it follows that $\bar{\sigma} < B$.

Proposition 4 does not yet allow us to draw conclusions about the change of θ as a response to an increase in x which is the ultimate purpose of our investigation. But the missing connection is easily established by taking (18) and (19) into account in (17) to obtain

$$\frac{\hat{\theta}}{1 - \theta} = \frac{m_1(\sigma_s - p_s \sigma_i) - m_o \sigma_c + \mu_i(1 - \sigma_i) + \mu_s(1 - \sigma_s)}{\mu_i \sigma_i + \mu_s \sigma_s - m_1(\sigma_s - p_s \sigma_i) + m_o \sigma_c} \cdot \hat{x} = \frac{1 - \bar{\sigma} + B}{\bar{\sigma} - B} \cdot \hat{x} \quad (20)$$

where $m_o, p_s, m_1, \mu_i, \mu_s, B$ and $\bar{\sigma}$ are as defined in (17) and (18), respectively.

The comparison of equations (6) and (20) shows that it is much more complex to determine the intertemporal changes of the emission tax share in the two-sector economy than in the one-sector economy. In the latter, $\hat{\theta}$ exclusively depends on the magnitude of the elasticity of

technical substitution, σ . In contrast, equation (20) tells us that in the two-sector economy $\hat{\theta}$ depends on several factors:

- the demand conditions (σ_c),
- the abatement technologies in both sectors (σ_i and σ_s),
- the difference in the emission intensity of sectoral production ($x_s > x_i$ via m_i).
- and the price of services in terms of the industrial good (p_s)

Closer inspection of (20) reveals

Proposition 5: Let $\sigma_i, \sigma_s, \sigma_c \in]0, \infty[$.

$$(a) \frac{\hat{\theta}}{\hat{x}} \begin{matrix} > 0 \\ < 0 \end{matrix} \Leftrightarrow \begin{cases} B \in]\bar{\sigma}-1, \bar{\sigma}[\\ B < \bar{\sigma}-1 \end{cases}$$

(b) If $m_i > \mu_s$, and if $B_o \in]\bar{\sigma}_o - 1, \bar{\sigma}_o[$, $B_o > 0$, is given in an initial situation, the sign of $\hat{\theta}/\hat{x}$ is changed from positive to negative by successively reducing the mean elasticity of substitution, $\bar{\sigma}$, while keeping the value of B at B_o .

(c) If $B_o \in]\bar{\sigma}_o - 1, \bar{\sigma}_o[$ is given in an initial situation, the sign of $\hat{\theta}/\hat{x}$ is changed from positive to negative by successively reducing the bias term, B , while keeping the value of $\bar{\sigma}$ at $\bar{\sigma}_o$.

(d) If $\sigma_c = 0$ and if the technologies Y^I and Y^S are the same, equation (20) coincides with equation (6).

$$(e) \frac{\hat{\theta}}{\hat{x}} \begin{matrix} \geq \frac{1-\bar{\sigma}}{\bar{\sigma}} \\ < \frac{1-\bar{\sigma}}{\bar{\sigma}} \end{matrix} \Leftrightarrow B \begin{matrix} \geq 0 \\ < 0 \end{matrix}$$

$$(f) \frac{d(\hat{\theta}/\hat{x})}{d\sigma_c} = -\frac{(1-\theta)m_o}{(\bar{\sigma}-B)^2} < 0;$$

$$(g) \frac{d(\hat{\theta}/\hat{x})}{d\sigma_s} = \frac{(1-\theta)(m_i - \mu_s)}{(\bar{\sigma}-B)^2} \begin{matrix} \geq 0 \\ < 0 \end{matrix} \Leftrightarrow m_i \begin{matrix} \geq \\ < \end{matrix} \mu_s;$$

$$(h) \frac{d(\hat{\theta}/\hat{x})}{d\sigma_i} = -\frac{(1-\theta)(\mu_i + m_i p_s)}{(\bar{\sigma}-B)^2} < 0.$$

To validate proposition 5a recall (from the proof of proposition 4) that $B > \bar{\sigma}$ is infeasible. In case of $B < \bar{\sigma}$ one has $\hat{\theta}/\hat{x} > 0$ iff $1 - \bar{\sigma} + B > 0$ or $B > \bar{\sigma} - 1$. Hence $\hat{\theta}/\hat{x} > 0$, iff $B \in]\bar{\sigma} - 1, \bar{\sigma}[$. Correspondingly, $\hat{\theta}/\hat{x} < 0$ iff $1 - \bar{\sigma} + B < 0$ or $B < \bar{\sigma} - 1$.

Proposition 5a is certainly the principal answer to our question how the emission tax share, θ , responds to an increase in the economy's capital intensity, x . The observations in proposition 5b - 5d help to better understand the constraints on B and $\bar{\sigma}$ that determine the sign of

$\hat{\theta}/\hat{x}$ according to proposition 5a. To see the rationale of proposition 5b, we write, for convenience of notation, $\sigma := (\sigma_c, \sigma_i, \sigma_s)$ and $B(\sigma) := m_1(\sigma_s - p_s\sigma_i) - m_o\sigma_c$ and assume that some triple σ_o is given satisfying $\bar{\sigma}_o := \mu_i\sigma_{io} + \mu_s\sigma_{so} > 0$ and $B_o := B(\sigma_o) \in]\bar{\sigma}_o - 1, \bar{\sigma}_o[\cap \mathfrak{R}_{++}$. Note that σ_o implies $\hat{\theta}/\hat{x} > 0$ owing to proposition 5a. Now consider the set $S := \{\sigma \in \mathfrak{R}_+ \mid B_o = m_1(\sigma_s - p_s\sigma_i) - m_o\sigma_c\}$. We solve $B_o = m_1(\sigma_s - p_s\sigma_i) - m_o\sigma_c$ for σ_s and substitute σ_s in $\bar{\sigma} = \mu_i\sigma_i + \mu_s\sigma_s$. This gives us

$$\bar{\sigma}(\sigma) := \frac{\mu_s B_o}{m_1} + \frac{\mu_s m_o}{m_1} \sigma_c + (\mu_i + \mu_s p_s) \sigma_i$$

$\bar{\sigma}(\sigma)$ is the mean elasticity of substitution that preserves $B = B_o$ because $\sigma \in S$ by construction. One obviously has $\bar{\sigma}(\sigma_o) = \bar{\sigma}_o$. Therefore, by reducing σ_i and /or σ_c , it is possible to select $\sigma \in S$ satisfying $\bar{\sigma}(\sigma) < \bar{\sigma}_o$. In fact, it is easy to see that $\bar{\sigma}(\tilde{\sigma}) < \bar{\sigma}(\sigma)$ for all $\sigma \in S$, if $\tilde{\sigma} = (\sigma_c = 0, \sigma_i = 0, \sigma_s = B_o/m_1)$ with $\bar{\sigma}(\tilde{\sigma}) = \mu_s B_o/m_1$. Since $\mu_s < m_1$ has been presupposed, it follows that $B_o > \bar{\sigma}(\tilde{\sigma})$. Thus we showed that there is a subset $\tilde{S} \subset S$, $\tilde{S} \neq \emptyset$, such that $B_o \notin]\bar{\sigma}(\sigma) - 1, \bar{\sigma}(\sigma)[$ and hence $\hat{\theta}/\hat{x} < 0$ for all $\sigma \in \tilde{S}$.

The comparative statics exercise performed in proposition 5b allows for the interesting special case to set $\sigma_{io} = 0$ so that $\bar{\sigma}(\sigma) = \mu\sigma_s$ for all $\sigma \in S$ for which $\bar{\sigma}(\sigma) < \bar{\sigma}(\sigma_o)$. In that case the reduction of $\bar{\sigma}$ is accomplished by reducing both σ_s and σ_c . The message of proposition 5b is intriguing because it is counter to the intuition shaped by the performance of the one-sector economy where reducing an initially high elasticity of substitution ($\sigma > 1$) turns θ/\hat{x} from negative to positive.

Another interesting and similarly unexpected insight is provided in proposition 5c. As in proposition 5b we start from some $B_o \in]\bar{\sigma}_o - 1, \bar{\sigma}_o[$ implying $\hat{\theta}/\hat{x} > 0$. Setting $B(\sigma_c) := m_1(\sigma_{so} - p_s\sigma_{io}) - m_o\sigma_c$ obviously yields $B(\sigma_{co}) = B_o$ and $B(\sigma_c) < B_o$ for all $\sigma_c > \sigma_{co}$. Since σ_c can arbitrarily be increased, there is $\sigma_{c1} > \sigma_{co}$ such that $B(\sigma_c) < \bar{\sigma}_o - 1$ for all $\sigma_c > \sigma_{c1}$ which yields $\hat{\theta}/\hat{x} < 0$. It should be emphasized that proposition 5c must not be misinterpreted to mean that any reduction of the bias term B reduces $\hat{\theta}/\hat{x}$ because, in general, changes in B will also change $\bar{\sigma}$. A similar qualification is necessary with respect to proposition 5b.

Proposition 5d follows immediately from observing that $\sigma_c = 0$, and $Y^i = Y^s$ (hence $\sigma_i = \sigma_s$ and $x_i = x_s$) imply $B = 0$.

Comparing the one-sector economy to the two-sector world with $\sigma_c \geq 0$ and $Y^i \neq Y^s$ suggests that the natural counterpart of the multiplier $(1 - \sigma)\sigma$ of the one-sector model is

$$\frac{1 - \bar{\sigma}}{\bar{\sigma}} = \frac{\mu_i(1 - \sigma_i) + \mu_s(1 - \sigma_s)}{\mu_i\sigma_i + \mu_s\sigma_s}$$

which in view of (6) is properly interpreted as a benchmark effect of \hat{x} on $\hat{\theta}$ in the two-sector economy. Equation (20) shows that, in general, $\hat{\theta}/(1-\theta)\hat{x}$ deviates from this benchmark effect owing to the sectoral technological divergences, $\sigma_i \neq \sigma_s$ and $x_s > x_i$, and to the demand substitution, $\sigma_c > 0$. The combined effect of both distortions is captured in B , and proposition 5e shows how alternative values of B translate into the divergence of $\hat{\theta}/\hat{x}$ and the benchmark effect $(1-\bar{\sigma})/\bar{\sigma}$.

Another obvious way to characterize the deviation of $\hat{\theta}/(1-\theta)\hat{x}$ from $(1-\bar{\sigma})\bar{\sigma}$ is to define $\bar{\sigma}^* := \bar{\sigma} - B$ and rewrite (20) as

$$\frac{\hat{\theta}}{(1-\theta)\hat{x}} = \frac{1-\bar{\sigma}^*}{\bar{\sigma}^*}.$$

Evidently, $\bar{\sigma}^*$ can be viewed as a distorted mean elasticity of technical substitution. Since $B > \bar{\sigma}$ is infeasible, one has, in fact $\bar{\sigma}^* \geq 0$. Note also that in this perspective $B = \bar{\sigma} - \bar{\sigma}^*$ is the bias of the 'true' mean elasticity of substitution, $\bar{\sigma}$, from its effective counterpart, $\bar{\sigma}^*$. This bias can be positive and negative which, in turn, makes the bias of $\hat{\theta}/(1-\theta)\hat{x}$ from $(1-\bar{\sigma})\bar{\sigma}$ positive and negative, respectively, as spelled out in proposition 5e.

Summing up, our inspection of (20) and its comparison to (6) showed that moving from the one-sector to the two-sector economy makes the response of the emission tax share to an increase in the aggregate capital intensity a lot more complex. The principal message still holds namely that the sign of $\hat{\theta}/\hat{x}$ depends on the sign of $1-\bar{\sigma}$ where the weighted mean elasticity of substitution, $\bar{\sigma} = \mu_i\sigma_i + \mu_s\sigma_s$, of the two-sector model appears to be the natural counterpart of the elasticity of substitution, σ , in the one-sector model. But, in general, $\hat{\theta}/(1-\theta)\hat{x}$ will diverge from $(1-\bar{\sigma})\bar{\sigma}$, owing to a demand substitution distortion ($\sigma_c > 0$) and to differences in sectoral technologies ($Y^i \neq Y^s$). $\hat{\theta}/(1-\theta)\hat{x} > (1-\bar{\sigma})\bar{\sigma}$ is the more likely,

- the smaller is the elasticity of demand substitution, σ_c ;
- the greater is σ_s relative to σ_i , if industry is more emission intensive in its production than the service sector ($x_s > x_i$);
- the smaller is σ_s relative to σ_i , if the service sector is more emission intensive in its production than industry ($x_i > x_s$).

Suppose the industrial sector is relative emission intensive ($x_s > x_i$), as assumed throughout the paper. A situation in which the increase in marginal abatement costs is greater in industry than in the service sector ($\sigma_i > \sigma_s$) forms an incentive to shift production from industry to services thus easing the environmental constraint and reducing the emission tax share. Conversely, if $\sigma_s > \sigma_i$, the substitution away from the emission intensive production is deterred by relatively heavy increase in marginal abatement costs in the service sector. In addition, substituting away from the emission intensive good is also stimulated by the possibility of demand substitution, the more so, the closer substitutes are services for industrial goods as seen by the

consumers. Given any sectoral technologies Y^I and Y^S , there is always σ_c , sufficiently large, such that $\hat{\theta}/(1-\theta)\hat{x} < 0$ even if $(1-\bar{\sigma})/\bar{\sigma} > 0$.

In concluding the analysis of the determinants of changes in θ in the two-sector economy, it is appropriate to point to the important link between changes of x and specific forms of technical change. It has been shown that the impact of technical change on θ through changes of x over time is similar to that studied in the one-sector economy (propositions 1 and 2). Therefore the detailed discussion of this issue in section 2 will not be repeated here.

3.3 Diagrammatic illustrations

To improve the understanding of our results we now supplement the preceding algebraic analysis by graphical means. In *figure 2*, the letters with subscript 1 represent the initial situation and the letters with subscript a, b, c, etc. refer to the allocation in the next period¹¹ after the economy's capital stock has been increased by Δk . In its lower part, B_1 determines the factor allocation in the factor box with origins O_s and O_i whose sides are \bar{e} (width) and k_1 (height). By construction, B_1 is a point on the efficiency line spanning from O_s to O_i which is the locus of all efficient factor combinations satisfying (13). Clearly, the strict concavity of this line reflects our assumption that the industry is relative emission intensive in its production.

Suppose now the capital stock increases by Δk expanding the factor box to \bar{e} times $(k_1 + \Delta k)$ with origins O_s and O'_i . The associated efficiency line passes through the points $O_s, B_a, B_a,$ and O'_i . Since we know that the new factor allocation is a point on this line, we first consider the special case where the sectoral emission intensities (and hence the capital intensities) remain unchanged. Clearly, this constellation is realized by moving from B_1 to B_a in the lower part of figure 2, implying the changes $\hat{e}_i \equiv \hat{\lambda}_i < 0$ and $\hat{x}_i = \hat{x}_s = 0$. Hence from (17)

$$\hat{\theta} = \frac{(1-\theta)\mu_i(x_s - x_i)}{x_i} \hat{\lambda}_i < 0.$$

This result is easily confirmed in figure 2 by noting first that the emission tax rate τ remains unchanged when moving from B_1 to B_a . Since the emission standard is fixed by assumption, the emission tax revenue $\tau\bar{e}$ is unchanged. To answer the question as to how the income $y_i + p_s y_s$ changes when moving from B_1 (first period) to B_a (second period), consider the transformation curves AB and CD in the upper part of figure 2 which are meant to be those implied by the efficiency lines $O_s O_i$ and $O_s O'_i$, respectively, in the lower part of that figure 2. The points P_1 and P_a on the transformation curves have the common property that their marginal rate of transformation is equal to p_{s1} . The straight lines EF and GH with slope p_{s1} measure total income at production points P_1 and P_a , respectively, for the following reason: Define $z_i := y_{i1} + p_{s1}y_{s1}$ as the total income associated to the point 1. Consequently, the algebraic form of EF is $y_i = z_i - p_{s1}y_s$. Since EF passes through the production point P_1 , it satisfies $y_{i1} = z_i - p_{s1}y_{s1}$, and therefore total income in the initial situation is

¹¹ In our algebraic analysis we used the concept of continuous time. But for the purpose of graphical illustration it is more intuitive to think about periods (of finite length) rather than of points in time.

$y_l = z_l = y_{l1} + p_{s1} y_{s1}$ measured by OE in figure 2. Correspondingly, total income is OG when the production point is P_a . Clearly, $OG > OE$ and therefore $y_a > y_l$ which is a general result, because the transformation curve CD lies strictly above AB . We conclude from $y_a > y_l$ and $\tau_a = \tau_l$ that $\theta_l > \theta_a$.

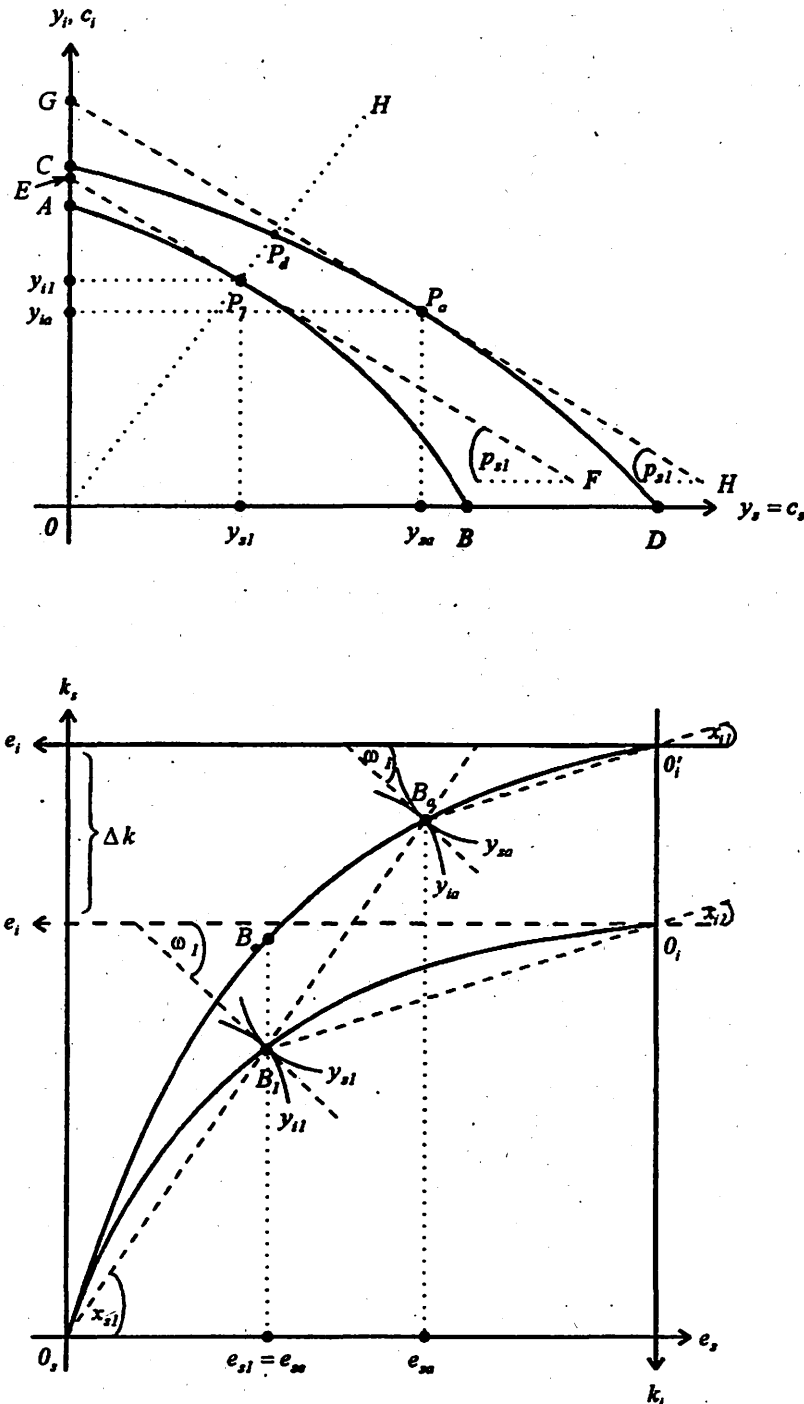


Figure 2: Emission tax revenues in a growing two-sector economy

So far, we clarified the impact of changes in λ_l on the emission tax share without having investigated the conditions under which a shift from P_1 to P_a in figure 2 takes place. Further insight is gained by focusing on the upper part of figure 2. To generate the consumption possibility curves from the respective production possibility curves AB and CD , we subtract from

the curve AB a fixed amount of net investment $\Delta k_1 > 0$ and from CD the amount $\Delta k_2 > 0$. The resultant consumption possibility curves have a similar shape as the production possibility curves.

For convenience of exposition, we now simply consider the lines AB and CD as representing those consumption possibility curves rather than the transformation curves and assign P_1 as the initial consumption point (satisfying $(U_i/U_s) = p_{s1}$) Since U is assumed to be homothetic (see section 3.2), the curvature of the indifference curves is measured by $\sigma_c \geq 0$, the elasticity of substituting services and industrial goods in consumption. If $\sigma_c = 0$, the consumption point is necessarily a point on the ray OH . Hence P_d will be chosen in the second period. For $\sigma_c = \infty$ the straight line EF represents an indifference curve. In case of such flat indifference curves, in the second period utility is maximized at P_a where the indifference curve GH is tangent to the consumption possibility curve CD . Hence P_a will be chosen in the second period. We showed above that $\theta_1 > \theta_a$, i. e. $\hat{\theta}/\hat{x} < 0$, and this result is in line with proposition 5a because B tends to $-\infty$ when σ_c tends to ∞ (see also proposition 5c). It is then straight forward from the graphical analysis that if σ_c is positive and finite the consumption point is located on the segment between P_d and P_a of the curve CD , and it is the closer to P_a the greater is σ_c .

Our graphical investigation of figure 2 thus leads us to conclude that the emission tax share shrinks ($\hat{\theta} < 0$) when moving from P_1 to P_a . Figure 3 restates this finding in a more compact way and demonstrates, moreover, the demand side impact (through the value of σ_c) on the sign and magnitude of $\hat{\theta}$.

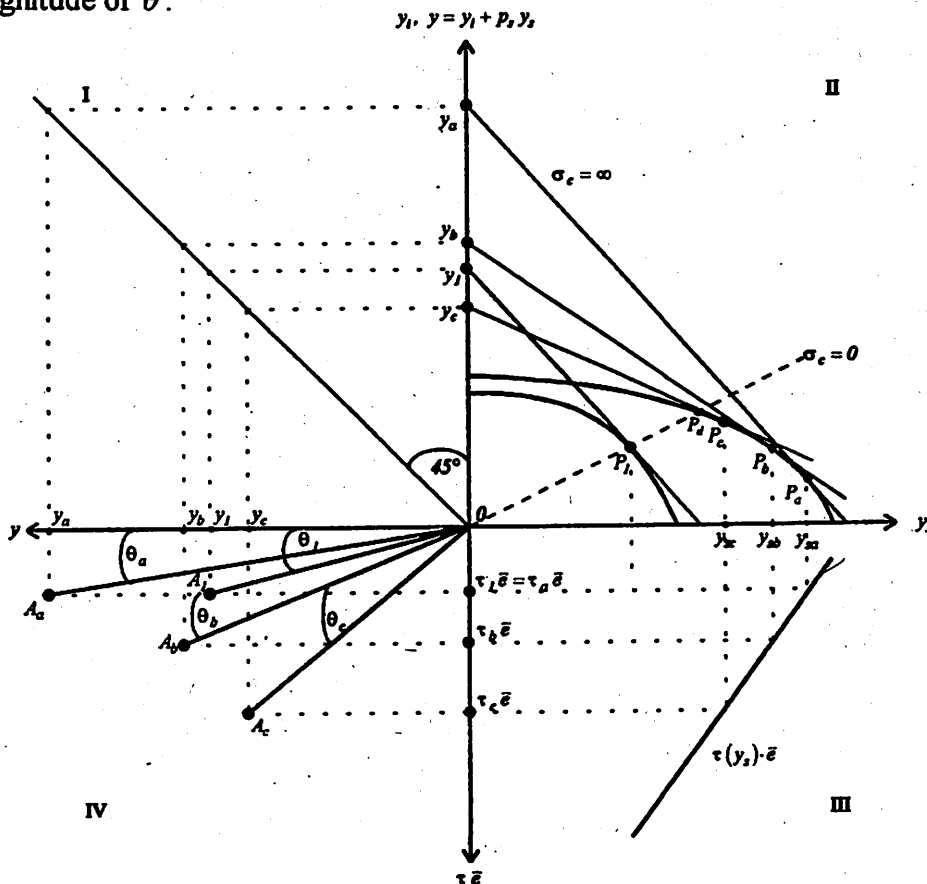


Figure 3: Emission tax shares in the growing two-sector economy

Quadrant II of figure 3 shows the same transformation curves as the upper part of figure 2, and the points P_1 , P_a and P_d are also taken over from figure 2. Suppose first that $\sigma_c = \infty$ so that the move is from P_1 to P_a . Since $\tau_1 = \tau_a$ and $y_a > y_1$, θ_1 and θ_a are found in quadrant IV of figure 3 as the slopes which the straight lines OA_1 and OA_a , respectively, have with respect to the y-axis. Quadrant III of figure 3 considers the inverse relationship between τ and y_s in case of efficient production.¹² We now turn to answering the question of how θ_1 changes when σ_c is positive but finite. In this case the production point P_1 is shifted to P_b or P_c , for example. As quadrant IV of figure 3 reveals, one gets $\theta_c > \theta_b > \theta_1 > \theta_a$. Indeed, figure 3 demonstrates for a specific constellation of production technologies that there is $\bar{\sigma}_c > 0$ such that $\hat{\theta} \geq 0$ if and only if $\sigma_c \leq \bar{\sigma}_c$. Hence our diagrammatic analysis helped to clarify the impact of the demand side on the emission tax share, and our findings in figure 3 are fully consistent with the algebraic results in proposition 5.

4. Concluding remarks

Our analysis showed that in a growing economy the emission tax revenues do not necessarily grow at the same rate as *GNP* which would be required to keep the tax emission share constant over time. In the one-sector economy the difference in growth rates simply turned out to depend on the (aggregate) elasticity of technical substitution: The easier, hence less costly, it is to avoid the emission of pollutants at the margin, the less expensive it is to satisfy the emission standard, and the more likely it is that the emission tax share shrinks.

In the two-sector economy this relationship still holds, in principle at least, but important qualifications have to be added: On the one hand, the elasticity of substituting industrial goods and services in consumption plays a role and the impact of both elasticities of technical substitution is asymmetric. The substitution elasticity in the industrial sector causes a distortion in the same direction as the elasticity of demand substitution while the substitution elasticity in the service sector works in the opposite direction.

The paper also presented an analysis of possible patterns of growth in an economy where the growth rate of the labor force is assumed to be zero, where capital accumulates and where different types of exogenous technical change are considered. The relevance of the time path of growth for the difference between the growth rates of *GNP* and emission tax revenues is obvious: Whenever the growing economy approaches a steady state equilibrium (including the possibility of zero growth) the growth rates of *GNP* and emission tax revenues converge. Otherwise they may be divergent for ever in either direction.

In the one-sector economy the emission tax share grows in case of economic growth if the increase in marginal abatement costs is sufficiently high i. e. if the pollution problem becomes increasingly obstinate over time. If the marginal abatement costs are not, or only weakly, increasing, then the constraint placed on the economy by the emission standard becomes less severe, the emission tax share shrinks. In the two sector economy the emission tax share is the more likely to grow in case of an increase in the economy's capital intensity, the smaller is the elasticity of demand substitution, the greater is the increase in marginal abatement costs in the

¹² Moving on the transformation curve towards the y-axis (increasing y_s) reduces both sectoral capital intensities which, in turn, diminishes τ .

less emission-intensive sector (services) and the greater it is in the other sector (industry). If the sectoral elasticities of substitution do not differ too much (which is plausible when the waste abatement technologies are of the end-of-the-pipe variety) then the emission tax share is the more likely to grow, the smaller is the elasticity of demand substitution.

If there is a general message including both the analysis of the one - and two-sector economy, then it is probably the observation, that the more difficult it becomes to avoid the emission of pollutants either by abating pollutants or by shifting the demand towards low-pollution goods the more likely it is that the emission tax revenue grows faster than *GNP*, and therefore the more reliable are emission taxes as a long-term source of tax revenues. From the revenue-raising point of view a particularly favorable scenario is the case of 'emission-saving' technical change, because in this case the emission tax share remains constant after the economy reached the steady state in which *GNP* grows as well as physical capital.

One of several simplifying assumptions made in this paper was the homotheticity of the utility function in the two-sector economy implying that the income elasticity of both goods is unity. Casual observations suggest that in the real world the income elasticity of services is greater than that of industrial goods. If this would be taken into account and if, moreover, services are less emission intensive in their production than industrial goods (as we assumed), then one would expect an additional structural shift in favour of the service sector with a tendency to reduce the (positive or negative) growth rate of the emission tax share.

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Appendix

Appendix A: Growth in the one-sector economy

The Hamiltonian associated to (3) is

$$H = U(c) + \mu \left[x(\hat{\kappa} - \hat{\alpha} - \delta) + \kappa Q(x) - \frac{\kappa c}{\alpha e} \right], \quad (a)$$

and a solution to this optimal control problem satisfies

$$L_c = U_c(c) - \frac{\kappa}{\alpha e} \mu = 0, \quad (b)$$

$$\hat{\mu} = \rho + \delta + \hat{\alpha} - \hat{\kappa} - \kappa Q_x(x). \quad (c)$$

Differentiation of (b) with respect to time yields $\hat{\mu} = \eta_{uc} \hat{c} + \hat{\alpha} - \hat{\kappa}$ which we combine with (c) to obtain

$$\hat{c} = \frac{\rho + \delta - \kappa Q_x(x)}{\eta_{uc}} = - \frac{\kappa Q_x(x) - \rho - \delta}{\eta_{uc}}. \quad (4)$$

To prove the proposition 1, each constellation of technical change must be separately considered.

(I) Let the *technical change be capital augmenting* ($\hat{\kappa} > 0, \hat{\alpha} = 0$) and suppose there is t_1 such that $\hat{x}_t \leq 0$ for all $t \geq t_1$. Then from (4)

$$c_{t_1} = - \frac{\kappa_{t_1} Q_x(x_{t_1}) - \rho - \delta}{\eta_{uc}}$$

If $\hat{c}_{t_1} < 0$ there is $t_2 > t_1$ such that $\hat{c}_t > 0$ for all $t \geq t_2$. If $\hat{c}_{t_1} > 0$, then $\hat{c}_t > 0$ for all $t > t_1$. But a time path of consumption with positive and strictly increasing \hat{c} is infeasible since at the same time $\hat{y}_t = (x_t Q_x / q_t) \hat{x}_t < 0$ for all $t \geq t_1$ (by assumption). It follows that a steady state ($\hat{x} = 0, \hat{\mu} = 0$) is not optimal and \hat{x}_t tends to be positive in the long run.

(II) Assume now, the *technical change is Hicks neutral* ($\hat{\alpha} = \hat{\kappa} > 0$) and suppose there is t_1 such that $\hat{x}_t \leq 0$ for all that $t \geq t_1$. Then we know from (4) that

$$\frac{d\hat{c}}{dt} = - \frac{\kappa(Q_x \hat{\kappa} + x Q_{xx} \hat{x})}{\eta_{uc}}$$

which is positive for $\hat{x} \leq 0$ for all $t > t_1$. Hence eventually $\hat{c} > 0$ and ever increasing. On the other hand, there is an upper bound on \hat{y} , since $\hat{y} = \hat{\alpha} + (x Q_x / q) \hat{x} \leq \hat{\alpha}$. For that reason, $\hat{x} \leq 0$ is not feasible 'for ever'. Hence \hat{x} tends to be positive in the long run.

(III) If the *technical change is 'emission saving'* ($\hat{\alpha} > 0, \hat{\kappa} = 0$) (2) and (4) are turned into

$$\dot{x} = Q(x) - (\hat{\alpha} + \delta)x - \frac{c}{\alpha \bar{e}} \quad \text{and} \quad \hat{c} - \hat{\alpha} = \frac{\rho - \delta - Q_x(x) - \hat{\alpha} \eta_{uc}}{\eta_{uc}}$$

$\dot{x} = 0$ requires $c/(\alpha \bar{e})$ to be constant. Hence the values c^* and x^* of a steady state ($\dot{x} = 0$) are uniquely determined by setting equal to zero both equations above. By means of a standard phase diagram it can be shown that both capital intensity, x , and consumption per efficiency unit of assimilative services, $c/(\alpha \bar{e})$ are strictly increasing [decreasing] while approaching the steady state, if the initial capital intensity is low [high].

(IV) Suppose finally that there is *no technical change at all* ($\hat{\alpha} = \hat{\kappa} = 0$). This limiting case of Hicks neutral technical change turns (2) into $\dot{x} = Q(x) - \frac{c}{\alpha \bar{e}} - \delta x$ so that $\hat{c} = 0$ for $\dot{x} = 0$ which requires to set $\rho + \delta = Q_x(x)$ in view of (4). Hence a steady state exists, and the dynamics are qualitatively the same as in case of technical change. This completes the proof of proposition 1.

Appendix B: Growth in the two-sector model

The Hamiltonian/Lagrangian associated to the optimal control problem (12) is

$$L = U[c_i, \alpha \bar{e} (1 - \lambda_i) Q^s(x_s)] + \pi [x - \lambda_i x_i - (1 - \lambda_i) x_s] + \mu \left[x(\hat{\kappa} - \hat{\alpha} - \delta) + \lambda_i \kappa Q^i(x_i) - \frac{\kappa c_i}{\alpha \bar{e}} \right]$$

and the pertinent marginal conditions are

$$\frac{\partial L}{\partial \lambda_i} = 0: \quad -\alpha \bar{e} q_s U_s + \pi(x_s - x_i) + \mu \kappa q_i = 0 \quad (d)$$

$$\frac{\partial L}{\partial c_i} = 0: \quad \mu = \frac{\alpha \bar{e}}{\kappa} U_i \quad (e)$$

$$\frac{\partial L}{\partial x_i} = 0: \quad \pi = \mu \kappa Q_x^i = \alpha \bar{e} Q_x^i U_i \quad (f)$$

$$\frac{\partial L}{\partial x_s} = 0: \quad \pi = \alpha \bar{e} Q_x^s U_s \quad (g)$$

$$\hat{\mu} = \rho + \delta + \hat{\alpha} - \hat{\kappa} - \kappa Q_x^i \quad (h)$$

The equations (d) - (h) contain the information

$$\frac{U_s}{U_i} = \frac{Q_x^i}{Q_x^s} = \frac{q_i - x_i Q_x^i}{q_s - x_s Q_x^s} \quad \text{and hence} \quad (k)$$

$$\omega_i(x_i) := \frac{Q^i(x_i) - x_i Q_x^i(x_i)}{Q_x^i(x_i)} = \frac{Q^s(x_s) - x_s Q_x^s(x_s)}{Q_x^s(x_s)} =: \omega_s(x_s) \quad (13)$$

By definition, the elasticity of substitution in sector v is $\sigma_v := \hat{x}_v / \hat{\omega}_v$. It follows immediately from (13), therefore, that

$$\sigma_s \hat{x}_i = \sigma_i \hat{x}_s \quad (\ell)$$

Equation (k) also contains the ratio $\frac{Q_x^i}{Q_x^s} =: p_s$, the price of services in terms of the industrial good, which in turn, equals the marginal rate of transformation. The first equality sign in (k) tells us that, exactly as in the one-period two-sector model, the marginal rate of substitution in consumption (U_s / U_i) must equal the marginal rate of transformation even though in the intertemporal context the consumption point is not on the production possibility curve, in general.

In direct analogy to the procedure in the pure theory of trade (e. g. Kemp 1969) we now want to show that if industrial goods are relatively emission intensive in production, then $(\hat{p}_s / \hat{x}_i) < 0$.

To this end we differentiate $p_s = Q_x^i / Q_x^s$ with respect to time which yields

$$\begin{aligned} \hat{p}_s &= \hat{Q}_x^i - \hat{Q}_x^s = \frac{x_i Q_{xx}^i}{Q_x^i} \hat{x}_i - \frac{x_s Q_{xx}^s}{Q_x^s} \hat{x}_s, \\ &= \frac{q_i - x_i Q_x^i}{Q_x^i} \cdot \frac{Q_x^i}{q_i} \cdot \frac{x_i q_i Q_{xx}^i}{Q_x^i (q_i - x_i Q_x^i)} \hat{x}_i - \frac{q_s - x_s Q_x^s}{Q_x^s} \cdot \frac{Q_x^s}{q_s} \cdot \frac{x_s q_s Q_{xx}^s}{Q_x^s (q_s - x_s Q_x^s)} \hat{x}_s, \\ &= \omega_i(x_i) \cdot \frac{Q_x^i}{q_i} \cdot (-1) \frac{1}{\sigma_i} \hat{x}_i - \omega_s(x_s) \cdot \frac{Q_x^s}{q_s} \cdot (-1) \frac{1}{\sigma_s} \hat{x}_s. \end{aligned}$$

The last equation can be further simplified by using the information $q_v = Q_x^v(\omega_v + x_v)$ (see section 2) and by considering, in addition, the equations (10), (13) and (ℓ). The result is

$$\hat{p}_s = \frac{\omega Q_x^i Q_x^s}{q_i q_s \sigma_i} (x_i - x_s) \hat{x}_i. \quad (\text{m})$$

From (m) $(\hat{p}_s / \hat{x}_i) < 0$ follows since $x_i < x_s$ by assumption.

To get further information about the properties of the optimal time path, we differentiate (e) with respect to time and use (h) to obtain

$$\hat{c}_i = - \frac{\kappa Q_x^i(x_i) - \rho - \delta}{\eta_{ui}}, \quad (\text{n})$$

where $\eta_{ui} := c_i U_{ii} / U_i$. Moreover, under the assumption that the utility function U is homothetic, there is $\sigma_c > 0$ such that $d(U_s / U_i) / (U_s / U_i) = \frac{\hat{c}_i - \hat{c}_s}{\sigma_c}$. Combining this equation

with (k) and (ℓ) implies

$$\hat{c}_i - \hat{c}_s = \frac{\sigma_c \omega Q_x^i Q_x^s}{q_i q_s \sigma_i} (x_i - x_s) \hat{x}_i. \quad (14)$$

A final piece of information is invoked by totally differentiating $x = \lambda_i x_i + \lambda_s x_s$ from (10) with respect to time:

$$\hat{x} = \frac{\lambda_i x_i}{x} (\hat{\lambda}_i + \hat{x}_i) + \frac{\lambda_s x_s}{x} (\hat{\lambda}_s + \hat{x}_s) \quad (p)$$

We also have $\hat{\lambda}_s = -(\lambda_i / \lambda_s) \hat{\lambda}_i$ because of $\lambda_i + \lambda_s = 1$ from (10) and $\hat{x}_s = (\sigma_s / \sigma_i) \hat{x}_i$ from (13). When these terms are substituted in (p) one gets, after some rearrangement of terms,

$$\hat{x} = \frac{\lambda_i x_i \sigma_i + \lambda_s x_s \sigma_s}{x \sigma_i} \hat{x}_i - \frac{\lambda_i (x_s - x_i)}{x} \hat{\lambda}_i. \quad (15)$$

With all this information at hand, we now proceed to investigate the optimal time path of \hat{x} for alternative specification of technical change. For that purpose it will turn out to be very helpful to consider

(i) that $\text{sign } \hat{x}_i = \text{sign } \hat{x}_s$ (from (l)) and (ii) that $\hat{x} \neq 0$ and $\sigma_c \in]0, \infty[$ implies $\text{sign } \hat{x} = \text{sign } \hat{x}_i$ (as shown in proposition 4a).

(I) Let the *technical change be capital augmenting* ($\hat{\kappa} > 0, \hat{\alpha} = 0$), and suppose there is t_1 such that $\hat{x}_i \leq 0$ for all $t \geq t_1$. If $\hat{x} = 0$ then (l) and (15) imply that either $(\hat{x}_i = \hat{x}_s = \hat{\lambda}_i = 0)$ or $(\hat{x}_i > 0, \hat{x}_s > 0, \text{ and } \hat{\lambda}_i > 0)$ or $(\hat{x}_i < 0, \hat{x}_s < 0, \text{ and } \hat{\lambda}_i < 0)$. If $\hat{x}_i \neq 0$ (and $\hat{x} = 0$) then x_i [or x_s] grows until $x_i = x$ and $e_i = \bar{e}$ [or $x_s = x$ and $e_s = \bar{e}$] is reached in which case \hat{x}_i or \hat{x}_s , respectively, tend towards zero. If $\hat{x}_i = 0$ (and $\hat{x} = 0$) then y_i is constant. But owing to (n) \hat{c}_i is increasing over time, becoming eventually positive. Suppose now, $\hat{x} < 0$ and hence $\hat{x}_i < 0$ and $\hat{x}_s < 0$. Then (n) induces \hat{c}_i to become positive, eventually. But $\hat{c}_s > \hat{c}_i > 0$ for $\hat{x}_i < 0$ because of (14), which is not feasible in the long run in view of a transformation curve shrinking towards the origin.

(II) Assume now the *technical change is Hicks neutral* ($\hat{\kappa} = \hat{\alpha} > 0$). If there is t_1 such that $\hat{x}_i \leq 0$ for all $t \geq t_1$, then (n) and (14) cannot be satisfied in the long run unless $\hat{c}_s > \hat{c}_i > 0$. Since η_{ui} does not grow unboundedly with growing (c_s / c_i) such a path is not sustainable.

(III) For the case that the *technical change is 'emission saving'* ($\hat{\alpha} > 0, \hat{\kappa} = 0$), $\hat{x}_i < 0$ for all $t > t_1, t_1 \geq 0$, would imply via (n) and (14) that $\hat{c}_s > \hat{c}_i > 0$ 'for ever' which is no feasible path. Conversely, if $\hat{x}_i > 0$ for all $t > t_2, t_2 \geq 0$, then $0 > \hat{c}_i > \hat{c}_s$ 'for ever' owing to (n) and (14) which is evidently suboptimal. Hence the question is whether the optimal time path converges to a steady state. $\hat{x} = 0$ and $\hat{\mu} = 0$ prevail (see (10) and (h)) if and only if

$$Q'_x(x_i) = \rho + \delta + \hat{\alpha} \quad \text{and} \quad \lambda_i Q'(x_i) - \frac{c_i}{\alpha \bar{a}} = x(\hat{\alpha} + \delta). \quad (q)$$

The first of these equations requires $\hat{x}_i = 0$, hence $\hat{\lambda}_i = 0$ and $\hat{c}_i = \hat{c}_s$ according to (17) and (14), respectively. Consequently the second equation requires $c_i / \alpha \bar{e}$ to be constant implying

$\hat{c}_i = \hat{c}_s = \hat{\alpha}$. Hence we showed that, if $\hat{x} = \hat{\mu} = 0$, such a state x^* is both feasible and optimal. We conjecture that it is optimal to monotonely approach this steady state x^* with $\hat{x} > 0$, if $x_0 < x^*$, and with $\hat{x} < 0$, if $x_0 > x^*$.

(IV) Suppose finally, there is *no technical change at all* ($\hat{\alpha} = \hat{\kappa} = 0$) and assume there is t_j such that $\hat{x}_t < 0$ [$\hat{x}_t > 0$] for all $t \geq t_j$. Then (n) and (14) induce $\hat{c}_s > \hat{c}_i > 0$ [$0 > \hat{c}_i > \hat{c}_s$] 'for ever' which is not sustainable [not optimal]. Hence, in the long run, a no-growth steady state x^* will prevail characterized by (q) with $\hat{\alpha} = 0$. We conjecture that it is optimal to monotonely approach this steady state x^* with $\hat{x} > 0$, if $x_0 < x^*$, and with $\hat{x} < 0$, if $x_0 > x^*$.

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