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Carbon Pricing, Technology Transition, and Skill-Based Development

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Abstract

We analyze the impact of carbon prices on human capital accumulation, sectoral change, and economic growth. In our framework output is produced with dirty and/or clean technologies using skilled and unskilled labor as inputs. Carbon policy affects technology selection which transmits incentives for human capital formation. We show that a temporary policy may be sufficient for a transition to a clean economy and that such a policy also stimulates economic growth. Moreover, in the presence of inter-country knowledge spillovers, a carbon policy in the North helps human capital formation in the South and induces South's transition to the clean steady state.

Keywords: Carbon pricing, education, clean and dirty technologies, temporary policies.

JEL Classification: *Q43, O47, Q56, O41*

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1 Introduction

1.1 Environment and Technology

Economic costs and the restriction of feasible technology sets tend to dominate public perception of environmental policies. Improvements in the natural environment as well as economic benefits, such as induced accumulation of human and knowledge capital, appear less imminent because they are distributed over a longer time horizon. In the case of climate policy, environmental benefits are spread globally which weakens policy efforts of countries and gives strong incentives for free-riding. Given these difficult conditions it becomes a strong requirement that policy instruments be carefully selected and fully assessed in all dimensions. Economists mostly agree that global carbon pricing allows reaching the internationally accepted temperature targets at minimal cost (Gollier and Tirole 2015). Also, a uniform carbon price may act as a focal point facilitating international climate negotiations (Weitzman 2014, Cramton et al. 2017). Finally, putting a price on carbon may guide economic development in a favorable way. The crucial dynamic effects of environmental policies were stressed in earlier contributions (Bovenberg and Smulders 1995, Bovenberg de Mooji 1997) but have received much less attention in the current climate policy literature. Nevertheless, a recent report on carbon pricing explains the role of education and skilled labour for the transition to green growth (High-Level Commission 2017, p. 49).[1] It explains that production using clean technologies is human capital-intensive so that education decisions become closely interlinked with the energy transition. In the same vein, an earlier report found that shortages of skilled labor may constrain the decarbonization process of an economy (World Bank 2012). As a consequence, by its impact on human capital accumulation, carbon pricing may not only be the cornerstone of climate policy but also act as a development policy, fostering technology switches and education of the labor force. This is where the present paper aims to make a contribution.

We study the impact of carbon prices on the selection of competing technologies and on human capital accumulation driving long-run economic development. The considered econ-

[1] The report concludes that the "restructuring process can be done quicker and more efficiently if it is supported by education, migration, and trade policies that accelerate technology transfers and innovation. Decarbonization poses the usual challenges for policy makers trying to facilitate the restructuring and reduce the labor market adjustment costs, including those derived from a changing skills mix" (High-Level Commission 2017, p. 49).

omy uses skilled and unskilled labor for production and has a dirty and a clean technology available to combine the inputs. The education process allowing individuals to acquire skills constitutes the central building block of our model. The basic mechanism of this building block relies on two empirical regularities which are well documented and widely used in the literature, namely the positive effect of human capital accumulation on TFP growth and positive intergenerational spillover. The setup provides a microeconomic foundation for the supply of skilled labor which adds an important element to technology-driven growth models. We show that introducing a carbon tax affects the technology choice which in turn transmits incentives for human capital accumulation. Specifically, an appropriate tax induces a transition to a cleaner sectoral mix possibly up to a fully clean economy while at the same time raising the skill level of the population. We find that a temporary policy may be sufficient to appropriately address environmental problems which is an attractive feature for policy making under the conditions of potentially strong opposition. Once the transition to the fully clean economy has been completed, the carbon tax may be totally eliminated. Thus, a transition to a clean steady-state equilibrium is compatible with a declining tax over time.

Another dimension of knowledge spillovers concerns technology, know-how and human capital transfer from the advanced to the developing economies, the so-called North-South spillover. We show that introduction of a carbon tax in the North promotes development in the South by boosting its human capital accumulation and growth in TFP, even without the South having to implement any carbon policy itself.

1.2 Contribution to the Literature

By distinguishing between clean and dirty production and by deriving long-lasting effects of temporary policies our paper is close to Acemoglu et al. (2012). While their contribution features directed technical change[2] we rely on human capital accumulation as an engine of transition and growth. We derive the quantity of skills in the economy endogenously and focus on a single final output (think of heating or transportation) which can be produced with dirty and/or clean technology (e.g. using fossil energies or renewables). The paper is linked

[2]A related earlier theoretical contribution is Smulders and de Nooij (2003); Aghion et al. (2016) show empirically that firms innovate more in clean technologies when they face higher tax-inclusive fuel prices.

to the literature deriving sectoral reallocation and growth effects induced by environmental policy; a survey is provided by Ricci (2007).[3] Bovenberg and de Mooji (1997) suggested a "double dividend" of environmental policy yielding both positive environmental and growth impacts.[4] While most of the theoretical models on environment and growth use physical or knowledge capital (e.g. Michel and Rotillon 1995) the contributions focusing on education are less numerous. Human capital as an engine of growth was incorporated into growth theory by Uzawa (1965). Its role was later emphasized by Lucas (1988). Recent years have witnessed a remarkable revival of interest in the role of human capital as a vital component of the process of economic growth (see e.g., Jones 2014, Lucas 2015, Manuelli and Seshadri 2014). An early adaptation of the Uzawa-Lucas growth model to environmental economics was provided by Hettich (1998) who derives a positive growth effect of environmental taxation which is a consequence of inputs being reallocated from (dirty) production to (clean) education. The effects of pollution and environmental policy on human capital accumulation are also analyzed in Bosi and Ragot (2013) who derive a positive relationship between pollution and working time (which competes with time for education). Adding to their contribution we introduce an explicit education decision for the acquisition of skills and provide closed-form solutions for all the cases based on different initial conditions. Empirical evidence on the link between the environment and human capital accumulation is provided by Sapci and Shogren (2017).

In the transition to a clean economy, human capital plays an important part not only for environmental policy but also when such a policy is lacking.[5] A series of recent contributions highlights the significant positive relationship between the state of the environment and individual well-being, including health but also labour productivity and human capital (Zivin and Neidell 2012 and 2013, and Zivin, Hsiang, and Neidell 2016). These authors conclude that, given the importance of health and human capital as drivers of economic growth, environmental conditions become an important factor of production and long-run development. The case of pollution- induced health shocks and their impact on growth has been analyzed in a theoretical paper by Bretschger and Vinogradova (2017).

[3]The conditions under which environmental regulation fosters innovation and competitiveness are surveyed by Ambec et al. (2013).

[4]An empirical study for OECD countries finds evidence for positive growth effects of increasing energy prices, see Bretschger (2015).

[5]The (negative) impact of temperature on economic growth is empirically tested by Dell et al. (2012).

The present paper is organized as follows. Section 2 presents our baseline model. Section 3 describes the equilibrium, its dynamics and the possible steady states. Section 4 presents our results with respect to the total output and effects of taxation. It also discusses the North-South set-up. Section 5 concludes.

2 Baseline Model

Two key building blocks of our model are agents, who make decisions about acquisition of human capital, and the production sector, which uses two types of technology (dirty and clean) to produce a homogeneous consumption good. We consider an infinite-horizon discrete-time economy where all agents are initially identical and possess identical preferences. The agents' decisions with respect to acquisition of education and skills translate into the aggregate stock of human capital in the economy, which in turn determines the ease at which human capital can be acquired by the next generation. Since the clean and the dirty production processes are assumed to differ in skill intensity, the stock of human capital will determine which technology prevails from the outset and how a transition from the dirty to a clean steady state can be accomplished via carbon policy and the associated process of human capital accumulation. Let us therefore turn first to the microfoundations of the latter.

2.1 The agents

At each time t there is a continuum of agents with measure normalized to 1. Each agent is initially identical and has a choice between becoming skilled or unskilled worker. Acquiring education comes at the expense of labor income. Individual i living in period t spends e_t of her time on acquiring advanced education, while the remaining time, $1 - e_t$, is spent on work. Each individual in the labor market can supply either one unit of unskilled labor or some amount of human capital. If the individual decides to be unskilled, she sets $e_t = 0$ and spends all her time working. If she decides to be a human capital supplier, she must spend some time on higher education. Her individual human capital ζ_t depends on the total stock of human capital at time $t-1$, H_{t-1}, and the time she spends on education, e_t:

$$\zeta_t = \mu(H_{t-1})\varphi(e_t),$$

where $\varphi : [0,1] \to \mathbb{R}_+$ and $\mu : \mathbb{R}_+ \to \mathbb{R}_+$ are increasing continuous strictly concave functions such that $\varphi(0) = 0$ and $\mu(0) > 0$. The *effective* amount of human capital she supplies on the labor market is

$$h_t := (1 - e_t)\zeta_t.$$

The function $\mu(\cdot)$ captures the idea that the total stock of human capital matters — people leaving in an educated society find it easier to acquire skills — though at a diminishing rate.

Suppose our individual decides to be educated. Then she first maximizes the effective amount of her human capital by solving the following problem:

$$\max_{e \in [0,1]} \mu(H_{t-1})\varphi(e)(1-e). \tag{1}$$

Since $\varphi(\cdot)$ is a concave function, this problem has a unique solution $\hat{e}$. Therefore, the effective amount of her human capital is

$$h_t = \psi(H_{t-1}) := \mu(H_{t-1})\varphi(\hat{e})(1-\hat{e}). \tag{2}$$

It is clear that $\psi(\cdot)$ is continuous, concave and increasing.

To decide whether to be skilled or unskilled, the individual compares the wages she earns in the two cases. If being skilled gives her a higher wage income than being unskilled, she decides to be skilled. If the wage of an unskilled worker is higher than the wage she would make as a skilled worker, she decides to be unskilled. Formally, let w_t^H be the prevailing skilled workers' wage per unit of human capital at time t and w_t^L be the prevailing wage for unskilled workers. Individual i decides to be educated if $w_t^H h_t > w_t^L$. If $w_t^H h_t < w_t^L$, then she decides not to be educated and to supply one unit of unskilled labor in the labor market. If $w_t^H h_t = w_t^L$, she is indifferent between being educated and uneducated.

Labor market equilibrium implies that[6]

$$w_t^H h_t = w_t^L.$$

2.2 Production

The economy produces one consumption good using two technologies, clean technology labeled by c and dirty technology labeled by d. The output Y_t^j in sector $j = c, d$ at time t is determined by

$$Y_t^j = A_t F^j(H_t^j, L_t^j),$$

where A_t is the total factor productivity (for simplicity, we assume that it is equal for both technologies), H_t^j and L_t^j are the inputs of effective human capital and unskilled labor in technology $j = c, d$. The two sectors are perfectly competitive and human capital and unskilled labor are fully mobile between them.

We assume that the dynamics of the total factor productivity is given by

$$A_t = G(H_{t-1})A_{t-1},$$

where $G(\cdot)$ is a continuous increasing function. The growth rate of TFP at time t depends positively on the amount of human capital accumulated by the economy up to (but not including) that time. However, none of our results below depend on the dynamics of A_t. Its role will become more prominent once we consider the dynamics of output in Section 4.

The function $F^j(H, L),\ j = c, d$, is continuous, twice continuously differentiable on $\mathbb{R}_{++}$, exhibits constant returns to scale, is strictly concave in each input and satisfies the Inada conditions. Sector c is assumed to be human-capital intensive. It follows that the marginal productivity of raw labor relative to human capital in sector c is lower than that in sector d. Defining $\eta := \frac{H}{L}$ and

$$\xi^j(\eta) = \frac{F_L^j(H, L)}{F_H^j(H, L)},$$

[6]We assume that all agents are identical in their ability to learn. Therefore in equilibrium the wages of unskilled and skilled agents are equal. If we assumed heterogeneity in ability to learn, the wage of unskilled workers would be equal to the wage of the least talented skill worker.

where $\xi^j : \mathbb{R}_{++} \to \mathbb{R}_{++}, j = c, d$, we may write

$$\xi^c(\eta) < \xi^d(\eta), \ \forall \eta > 0.$$

These functions are well-defined due to the constant returns to scale of the functions $F^j(H, L), \ j = c, d$. Moreover, since $F^j(H, L), \ j = c, d$, are twice continuously differentiable on $\mathbb{R}_{++}$ and strictly concave in each input, the functions $\xi^j(\cdot)$ are differentiable and increasing. For example, if

$$F^j(H, L) = a^j H^{\alpha^j} L^{1-\alpha^j}, \ j = c, d \tag{3}$$

(with $\alpha^c > \alpha^d$) then

$$\xi^j(\eta) = \frac{1 - \alpha^j}{\alpha^j} \eta, \ j = c, d.$$

We turn next to the characterization of the equilibrium in our economy. Further, we will assume that a carbon tax $0 \leq \tau < 1$ is imposed on the dirty output. The collected tax is redistributed in a lump sum way.

3 Equilibrium

3.1 Characterization

We assume that Let L_t be the number of unskilled agents at time t and h_t the effective human capital of a skilled agent. Then the total stock of effective human capital is $H_t = (1 - L_t)h_t$.

Definition 1 *Given the carbon tax τ and the stock of human capital H_{t-1}, a time-t τ-equilibrium is defined by the following five conditions:*

1. $A_t F^c(H_t^c, L_t^c) - [w_t^H H_t^c + w_t^L L_t^c] = \max_{H,L}\{A_t F^c(H, L) - [w_t^H H + w_t^L L]\} = 0,$

2. $(1-\tau)A_t F^d(H_t^d, L_t^d) - [w_t^H H_t^d + w_t^L L_t^d] = \max_{H,L}\{(1-\tau)A_t F^d(H, L) - [w_t^H H + w_t^L L]\} = 0,$

3. $h_t = \psi(H_{t-1}),$

4. $w_t^L = w_t^H h_t$,

5. $H_t^c + H_t^d = H_t = (1 - L_t)h_t,\ L_t^c + L_t^d = L_t$.

These conditions have the standard interpretation, namely the profits in clean and dirty sectors are maximized (and equal to zero due to our assumption of competitiveness); the human capital is optimally supplied; the per-skill wage rates are equalized; and labor markets for skilled and unskilled labor clear. Note that in equilibrium, the shares of both skilled and unskilled individuals in the population are positive. Scenarios where all agents are skilled or all agents are unskilled are not feasible. Indeed, if all agents decided to be unskilled, then the wage paid to skilled workers would be so high compared with the wage of unskilled workers that all unskilled agents would have incentives to become skilled. Conversely, if all agents decided to be skilled, then the wage rate of unskilled workers would be so high that each skilled agents would prefer to be unskilled.

Using a traditional argument, it can be shown that, in *time-t τ-equilibrium*,

$$F^c(H_t^c, L_t^c) + (1-\tau)F^d(H_t^d, L_t^d) = \mathcal{F}(\tau, H_t, L_t)$$

and

$$w_t^H = A_t \mathcal{F}_H(\tau, H_t, L_t),\ w_t^L = A_t \mathcal{F}_L(\tau, H_t, L_t),$$

where

$$\mathcal{F}(\tau, H, L) := \max_{H^c, L^c, H^d, L^d} \{F^c(H^c, L^c) + (1-\tau)F^d(H^d, L^d) \mid H^c + H^d \leq H,\ L^c + L^d \leq L\}. \quad (4)$$

For any given $0 \leq \tau < 1$, the function $\mathcal{F}(\tau, H, L)$ is differentiable in (H, L) on $\mathbb{R}^d_{++}$ and concave (but is not strictly concave in each input) and exhibits constant returns to scale. In time-t τ-equilibrium, $F^c(H_t^c, L_t^c)$ shows the normalized by the total factor productivity (normalized for short) clean output, $F^d(H_t^d, L_t^d)$ the normalized dirty output and $\mathcal{F}(\tau, H_t, L_t)$ the normalized post-tax output (= normalized total output if $\tau = 0$).

Let $\xi(\tau, \eta)$ denote the ratio of the marginal productivity of unskilled labor to that of human capital:

$$\xi(\tau, \eta) := \frac{\mathcal{F}_L(\tau, H, L)}{\mathcal{F}_H(\tau, H, L)}.$$

The function $\xi(\tau, \eta)$ is well-defined on $R_{++} \times R_{++}$ because for any $0 \le \tau < 1$, the function $\mathcal{F}(\tau, H, L)$ has constant returns to scale in (H, L). In the next step, summarized in the Remark 1, we solve for the equilibrium values of skilled and unskilled labor in the economy as functions of ξ.

Remark 1 *Consider the maximization problem*

$$\max_{L,H} \mathcal{F}(\tau, H, L) \ s.t. \ \frac{H}{h} + L = 1,$$

where $h > 0$ is given. Necessary and sufficient conditions for optimality for this problem are

$$h = \xi(\tau, H/L), \ \frac{H}{h} + L = 1.$$

Therefore, its solution is given by

$$L = \frac{\xi(\tau, \eta^*)}{\xi(\tau, \eta^*) + \eta^*}, \ H = \frac{\xi(\tau, \eta^*)\eta^*}{\xi(\tau, \eta^*) + \eta^*},$$

where η^* is the solution to the following equation:

$$h = \xi(\tau, \eta).$$

It is clear that the maximum value of this problem is an increasing function of h.

Market clearing in the human capital and unskilled labor markets implies

$$w_t^L / w_t^H = \xi(\tau, \eta_t), \quad \eta_t := H_t / L_t. \tag{5}$$

Function $\xi(\cdot,\cdot)$ will turn out to be crucial for describing the equilibrium dynamics, therefore we shall analyze it in more detail. First, consider the unit cost functions:

$$c^c(\omega^H,\omega^L) := \min_{H,L}\{\omega^H H + \omega^L L \mid F^c(H,L) \geq 1\}, \tag{6}$$

$$c^d(\tau,\omega^H,\omega^L) := \min_{H,L}\{\omega^H H + \omega^L L \mid (1-\tau)F^d(H,L) \geq 1\}, \tag{7}$$

and consider the following system of two equations in ω^H and ω^L:

$$\begin{cases} c^c(\omega^H,\omega^L) = 1, \\ c^d(\tau,\omega^H,\omega^L) = 1, \end{cases} \tag{8}$$

and denote its unique solution by $(\omega^H(\tau),\omega^L(\tau))$. It is clear that *the ratio $\omega^L(\tau)/\omega^H(\tau)$ is a continuous decreasing function of τ such that $\omega^L(\tau)/\omega^H(\tau) \to 0$ as $\tau \to 1$.*

Let, for a given $0 \leq \tau < 1$, the vectors $(\hat{H}^c(\tau),\hat{L}^c(\tau))$ and $(\hat{H}^d(\tau),\hat{L}^d(\tau))$ be the solutions to, respectively, problems (6) and (7) at $(\omega^H,\omega^L) = (\omega^H(\tau),\omega^L(\tau))$. It is clear that for the given $0 \leq \tau < 1$, "the cone of diversification" is spanned by these two vectors.

Denote

$$\hat{\eta}^j(\tau) := \hat{H}^j(\tau)/\hat{L}^j(\tau), \; j = c,d.$$

Since good c is human capital-intensive, we have

$$\hat{\eta}^c(\tau) > \hat{\eta}^d(\tau).$$

Then, according to the factor price equalization theorem,

$$\xi(\tau,\eta) = \xi^d(\eta), \; \eta \leq \hat{\eta}^d(\tau),$$

$$\xi(\tau,\eta) = w^L(\tau)/w^H(\tau), \; \hat{\eta}^d(\tau) \leq \eta \leq \hat{\eta}^c(\tau).$$

$$\xi(\tau,\eta) = \xi^c(\eta), \; \eta \geq \hat{\eta}^c(\tau).$$

Therefore, $\hat{\eta}^j(\tau),\ j = c, d$, is the solution to the following equation:

$$\xi^j(\eta) = \omega^L(\tau)/\omega^H(\tau),\ j = c, d. \tag{9}$$

Thus,

$$\xi(\tau, \eta) = \begin{cases} \xi^d(\eta), & \text{if} \quad \eta < \hat{\eta}^d(\tau) \\ \omega^L(\tau)/\omega^H(\tau), & \text{if} \quad \hat{\eta}^d(\tau) \leq \eta \leq \hat{\eta}^c(\tau) \\ \xi^c(\eta), & \text{if} \quad \eta > \hat{\eta}^c(\tau) \end{cases} . \tag{10}$$

Figure 1 shows the function $\xi(\tau, \cdot)$ for a given $0 \leq \tau < 1$ and illustrates the solution to problem (4). We can formulate the following proposition describing the structure of time-t τ-equilibrium.

Proposition 1 *In time-t τ-equilibrium:*

- *if $\eta_t \leq \hat{\eta}^d(\tau)$, only the dirty technology is used, the output of the clean technology is zero, i.e. $\mathcal{F}(\tau, H_t, L_t) = (1 - \tau)F^d(H_t, L_t)$;*
- *if $\hat{\eta}^d(\tau) < \eta_t < \hat{\eta}^c(\tau)$, the output of both technologies is positive;*
- *if $\eta_t \geq \hat{\eta}^c(\tau)$, only the clean technology is used, the output of the dirty technology is zero, i.e. $\mathcal{F}(\tau, H_t, L_t) = F^c(H_t, L_t)$.*

Note that since $\omega^L(\tau)/\omega^H(\tau)$ is continuous and decreasing in τ, the functions $\hat{\eta}^j(\tau),\ j = 1, 2$, are also continuous and decreasing.

3.2 Equilibrium dynamics

Assuming that at time $t - 1$ the economy is in equilibrium, we can rewrite (2) as

$$h_t = \phi(\tau, \eta_{t-1}).$$

where

$$\phi(\tau, \eta) := \psi\left(\frac{\xi(\tau, \eta)\eta}{\xi(\tau, \eta) + \eta}\right).$$

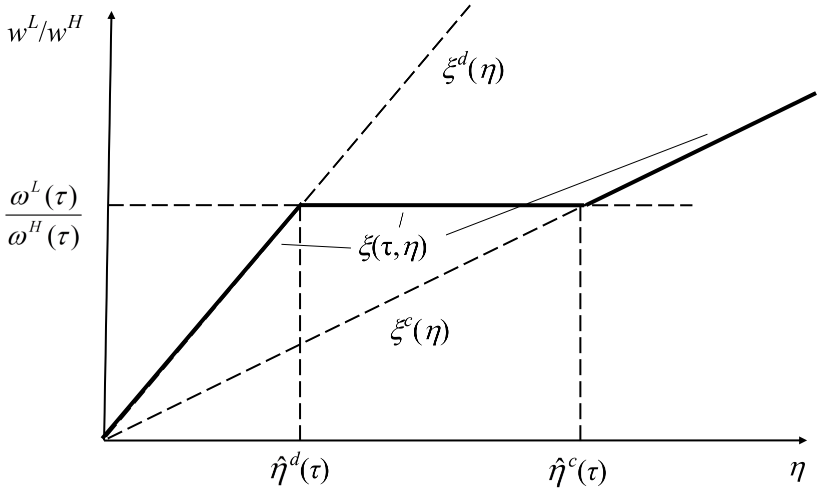

Figure 1

It is not difficult to verify that for any $0 \leq \tau < 1$, $\phi(\tau, \eta)$ is increasing in η and that

$$\phi(\tau,\eta) = \begin{cases} \psi\left(\dfrac{\xi^d(\eta)\eta}{\xi^d(\eta)+\eta}\right), & \text{if} \quad \eta < \hat{\eta}^d(\tau) \\ \psi\left(\dfrac{\omega^L(\tau)\eta}{\omega^L(\tau)+\omega^H(\tau)\eta}\right), & \text{if} \quad \hat{\eta}^d(\tau) \leq \eta \leq \hat{\eta}^c(\tau) \\ \psi\left(\dfrac{\xi^c(\eta)\eta}{\xi^c(\eta)+\eta}\right), & \text{if} \quad \eta > \hat{\eta}^c(\tau) \end{cases}.$$

Note that

$$\psi\left(\frac{\xi^d(\eta)\eta}{\xi^d(\eta)+\eta}\right) < \psi\left(\frac{\xi^c(\eta)\eta}{\xi^c(\eta)+\eta}\right)$$

Taking account of (5), we can rewrite the labor-market equilibrium condition $w_t^L = w_t^H h_t$ as

$$h_t = \xi(\tau, \eta_t). \tag{11}$$

Therefore,

$$\xi(\tau, \eta_t) = \phi(\tau, \eta_{t-1}). \tag{12}$$

It is clear that a time-t equilibrium is fully characterized by the value of η_t. Therefore, for short, we will call a sequence $(\eta_t)_{t=0}^{\infty}$ determined by (12) a *τ-equilibrium path* starting from η_0.

Here it is assumed that we are given $H_{-1} > 0$. Hence $h_0 = \psi(H_{-1})$ and η_0 is found as a solution to the equation $h_0 = \xi(\tau, \eta)$. If $h_0 \neq \omega^L(\tau)/\omega^H(\tau)$, η_0 is uniquely determined. When $h_0 < \omega^L(\tau)/\omega^H(\tau)$, the economy uses only the dirty technology and when $h_0 > \omega^L(\tau)/\omega^H(\tau)$, the economy uses only the clean technology.

3.3 Steady states

In this section we turn to the discussion of possible steady states in this economy.

Definition 2 *A solution to the equation $\xi(\tau, \eta) = \phi(\tau, \eta)$ in η is called a τ-steady-state equilibrium (τ-SSE).*

To provide a complete characterization of SSE and the dynamics of equilibrium paths we make the following additional assumption:

Assumption 1

$$\frac{d}{d\eta}\psi\left(\frac{\xi^j(\eta)\eta}{\xi^j(\eta)+\eta}\right) < \frac{d}{d\eta}\xi^j(\eta), \;\; \eta > 0, \;\; j = c, d.$$

Assumption 1 essentially requires that the slope of the $\psi(\cdot)$ function should be smaller than the slope of the $\xi(\cdot)$ function along the clean and the dirty subsets. This guarantees stability of the two equilibria in which the economy is specialized (i.e. either clean or dirty). If the production functions are Cobb-Douglas, i.e. given by (3), then

$$\psi\left(\frac{\xi^j(\eta)\eta}{\xi^j(\eta)+\eta}\right) = (1-\alpha^j)\eta, \quad \eta > 0, \;\; j = c, d,$$

and the assumption simplifies to

$$\psi'[(1-\alpha^j)\eta] < \frac{1}{\alpha^j}, \quad \eta > 0, \;\; j = c, d.$$

It follows from Assumption 1 that for $j = c, d$, the equation

$$\psi\left(\frac{\xi^j(\eta)\eta}{\xi^j(\eta)+\eta}\right) = \xi^j(\eta),$$

has at most one solution. In what follows we assume that it exists and denote it by $\bar{\eta}^j$. Clearly,

$$\bar{\eta}^d < \bar{\eta}^c. \tag{13}$$

Now we can show that there are at most three τ-SSE in our model:

1. A *dirty SSE* $\eta = \bar{\eta}^d$, in which only the dirty technology is used. In this SSE, the number of unskilled workers is $\bar{L}^d = \dfrac{\xi^d(\bar{\eta}^d)}{\xi^d(\bar{\eta}^d) + \bar{\eta}^d}$, the stock of human capital is $\bar{H}^d = \dfrac{\xi^d(\bar{\eta}^d)\bar{\eta}^d}{\xi^d(\bar{\eta}^d) + \bar{\eta}^d}$, the growth rate is $G(\bar{H}^d)$ and the total output normalized by the total factor productivity is $F^d(\bar{H}^d, \bar{L}^d)$. If $\eta = \bar{\eta}^d$ is a τ-SSE, it is locally or globally asymptotically stable.

2. A *clean SSE* $\eta = \bar{\eta}^c$, in which only the clean technology is used. In this equilibrium, the number of unskilled workers is $\bar{L}^c = \dfrac{\xi^c(\bar{\eta}^c)}{\xi^c(\bar{\eta}^c) + \bar{\eta}^c}$, the stock of human capital is $\bar{H}^c = \dfrac{\xi^c(\bar{\eta}^c)\bar{\eta}^c}{\xi^c(\bar{\eta}^c) + \bar{\eta}^c}$, the growth rate is $G(\bar{H}^c)$ and the total output normalized by the total factor productivity is $F^c(\bar{H}^c, \bar{L}^c)$. If $\eta = \bar{\eta}^c$ is a τ-SSE, it is locally or globally asymptotically stable.

3. An intermediate SSE, in which both technologies are used. This equilibrium, if it exists, is unstable.

Observe that the position of the dirty and the clean SSE does not depend on τ, while the position of the diversified SSE does.

Proposition 2 *1) If*

$$\frac{\omega^L(\tau)}{\omega^H(\tau)} > \xi(\bar{\eta}^c), \tag{14}$$

then the dirty SSE $\eta = \bar{\eta}^d$ is the unique τ-SSE and any τ-equilibrium path converges to it.

2) If

$$\xi(\bar{\eta}^d) < \frac{\omega^L(\tau)}{\omega^H(\tau)} < \xi(\bar{\eta}^c), \tag{15}$$

then there are three τ-SSE:

- *The dirty SSE $\eta = \bar{\eta}^d$.*
- *An intermediate SSE $\eta = \eta^m(\tau)$, where $\eta^m(\tau)$ lies between $\hat{\eta}^d(\tau)$ and $\hat{\eta}^c(\tau)$.*
- *The clean SSE $\eta = \bar{\eta}^c$.*

The dirty and the clean SSE, $\eta = \bar{\eta}^d$ and $\eta = \bar{\eta}^c$, are locally asymptotically stable and the equilibrium $\eta = \eta^m(\tau)$ is unstable. More precisely:

- *if $\phi(\tau, \eta_0) < \frac{\omega^L(\tau)}{\omega^H(\tau)}$, then the τ-equilibrium path starting from η_0 is dirty (i.e. only the dirty technology is used from the beginning) and it converges to $\bar{\eta}^d$.*
- *if $\phi(\tau, \eta_0) > \frac{\omega^L(\tau)}{\omega^H(\tau)}$, then the τ-equilibrium path starting from η_0 is clean (i.e. only the clean technology is used from the beginning) and it converges to $\bar{\eta}^c$.*

3) If

$$\frac{\omega^L(\tau)}{\omega^H(\tau)} < \xi(\bar{\eta}^c), \tag{16}$$

then $\eta = \bar{\eta}^c$ is the unique τ-SSE and any τ-equilibrium path converges to it.

The three cases described in the above proposition are illustrated in Figures 2 - 4 for the most interesting case $\tau = 0$.

As was noted above, on an equilibrium path $(\eta_t)_{t=0}^{\infty}$ at time t only the dirty technology is used if $\frac{\omega^L(\tau)}{\omega^H(\tau)} > \xi(\eta_t) = \phi(\tau, \eta_{t-1})$ and only the clean technology is used if $\frac{\omega^L(\tau)}{\omega^H(\tau)} < \xi(\eta_t) = \phi(\tau, \eta_{t-1})$. It follows that in the case where (14) holds true and the equilibrium path converges to the dirty SSE, it may be that, paradoxically, initially the clean technology is used but the economy's initial conditions set it on the path of human capital decumulation. In the case where (16) holds true and the equilibrium path converges to the clean SSE, it may be that initially the dirty technology is used but the initial conditions set the economy on the path of human capital accumulation. In the case where (15) holds true and $\frac{\omega^L(\tau)}{\omega^H(\tau)} \neq \xi(\eta_0)$, the equilibrium path is either clean or dirty depending on whether $\frac{\omega^L(\tau)}{\omega^H(\tau)} > \xi(\eta_0)$ or $\frac{\omega^L(\tau)}{\omega^H(\tau)} < \xi(\eta_0)$.

4 Equilibrium GDP and Carbon Tax

4.1 Comparing Clean and Dirty Output Levels

In this section we analyze the effect of introducing a carbon tax (a tax on dirty output) on the level of GDP and on its growth rate. By our assumption about the dynamics of the total factor productivity, its growth rate in period $[t, t+1]$ is increasing in η_t for any time-t τ-equilibrium. From (13) it also follows that *the rate of growth of the economy in the clean SSE is higher then*

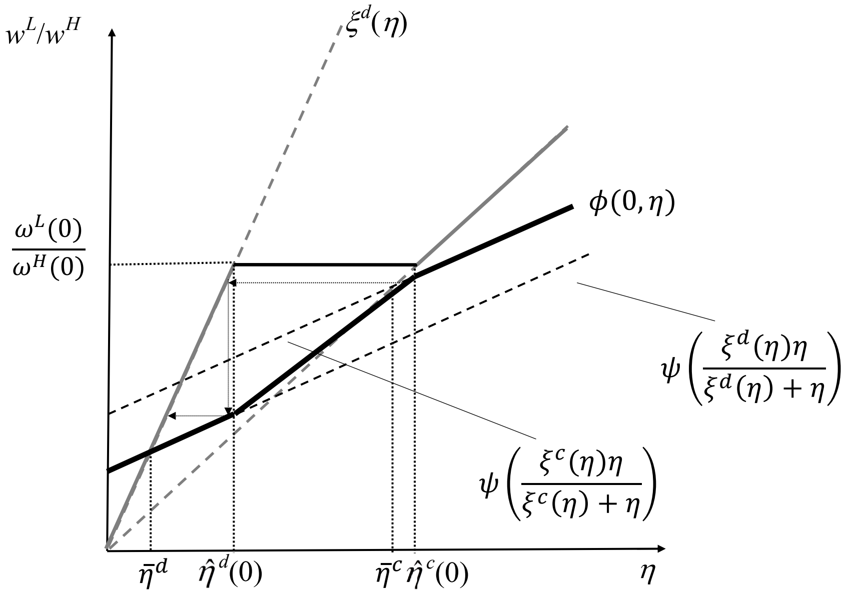

Figure 2

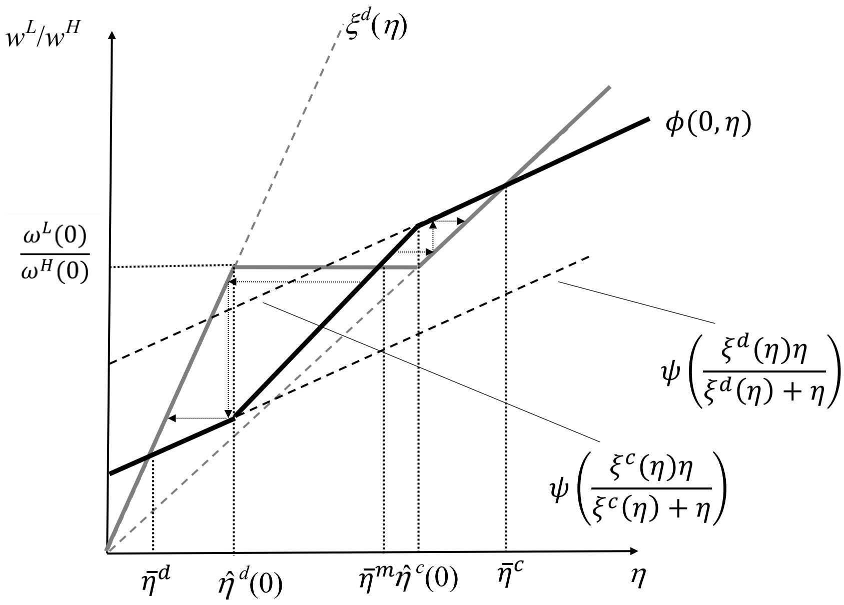

Figure 3

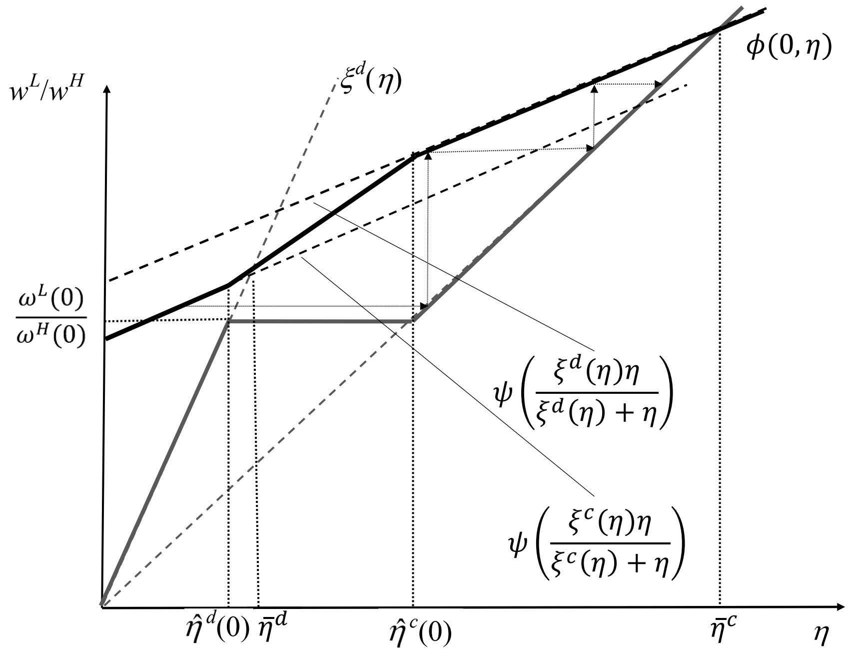

Figure 4

in the dirty equilibrium. This is a growth effect of human capital accumulation. In addition, there is a second, level, effect of human capital accumulation. Taking account of **Remark 1**, (H_t, L_t) given by

$$L_t = \frac{\xi(\tau,\eta_t)}{\xi(\tau,\eta_t)+\eta_t}, \; H_t = \frac{\xi(\tau,\eta_t)\eta_t}{\xi(\tau,\eta_t)+\eta_t}. \tag{17}$$

and in time-t τ-equilibrium, $\mathcal{F}(\tau, H_t, L_t)$ is increasing in $\xi(\tau,\eta_t)$. For $\eta_t \leq \hat{\eta}^d(\tau)$ (where only the dirty technology is used and $\mathcal{F}(\tau, H_t, L_t) = (1-\tau)F^d(H_t, L_t))$ and for $\eta_t \geq \hat{\eta}^d(\tau)$ (where only the clean technology is used and $\mathcal{F}(\tau, H_t, L_t) = F^c(H_t, L_t))$, the normalized total output is increasing in η_t. On the interval $[\hat{\eta}^d(\tau), \hat{\eta}^c(\tau)]$ the post-tax normalized output is constant. Therefore, the normalized total output is constant for all η_t in the interval $[\hat{\eta}^d(\tau), \hat{\eta}^c(\tau)]$ if $\tau = 0$, and decreasing in η_t on this interval if $\tau > 0$. Thus we can formulate the following proposition.

Proposition 3 *A clean* 0*-equilibrium path provides a higher level of the total output at each time than a dirty* 0*-equilibrium path. At the same time, if* $\tau > 0$*, then the total output in a clean* τ*-equilibrium path can be lower for some initial period of time than in a dirty* τ*-*

equilibrium path. In the long run, because of the growth effect, the total output on a clean path will be higher than on a dirty path.

As for SSE, we can formulate the following

Proposition 4 *If both $\eta = \bar{\eta}^d$ and $\eta = \bar{\eta}^c$ are 0-SSE (if $\xi(\bar{\eta}^d) < \frac{\omega^L(0)}{\omega^H(0)} < \xi(\bar{\eta}^c)$), then the normalized total output in the clean SSE is higher then in the dirty equilibrium (irrespective of τ). If the clean SSE $\eta = \bar{\eta}^c$ is not a 0-SSE, then the normalized total output in the clean SSE is smaller then in the dirty equilibrium (irrespective of τ).*

4.2 Taxing Dirty Output and Switching to Clean Technology

In the case where the dirty SSE is the only 0-SSE (and hence the clean SSE is not a 0-SSE), we can impose a tax $\tau > 0$ on the dirty output in such a way that the clean SSE becomes a τ-SSE (see Fig. 5). To see this graphically, suppose that 0-SSE is the one depicted in Fig. 2. Then suppose that a positive τ is introduced. This results in a downward shift of $\frac{\omega^L(\tau)}{\omega^H(\tau)}$ schedule and eventually leads to a situation depicted in Fig. 3, with an unstable diversified equilibrium. A still larger τ will lead to a situation in Fig. 4, where the clean equilibrium is stable. Note that the process of convergence to the clean SSE is accompanied by accumulation of human capital. Moreover, once the equilibrium is reached, there is no longer a need to maintain a positive carbon tax on dirty output. We may formulate the following proposition.

Proposition 5 *If $\frac{\omega^L(0)}{\omega^H(0)} > \phi(0, \bar{\eta}^c)$ and hence the clean SSE $\eta = \bar{\eta}^c$ is not a 0-SSE, then there exists $\underline{\tau} > 0$ such that $\eta = \bar{\eta}^c$ is a τ-SSE for any $\tau > \underline{\tau}$.*

Moreover, if we impose a tax on the dirty technology, the domain of convergence to the clean equilibrium widens.

Proposition 6 *For any initial state $\eta_0 > 0$ there exists $\underline{\tau}(\eta_0) \geq 0$ such that for any $\tau \geq \underline{\tau}(\eta_0)$, the τ-equilibrium path starting from η_0 is clean and converges to the clean SSE.*

It should be noted that if $\frac{\omega^L(0)}{\omega^H(0)} < \phi(0, \bar{\eta}^c)$ and, moreover, $\frac{\omega^L(0)}{\omega^H(0)} < \phi(0, \eta_0)$, then there is no need to impose a tax on the dirty output because the 0-equilibrium path starting from η_0 is clean and converges to the clean SSE.

The next proposition follows from Proposition 3

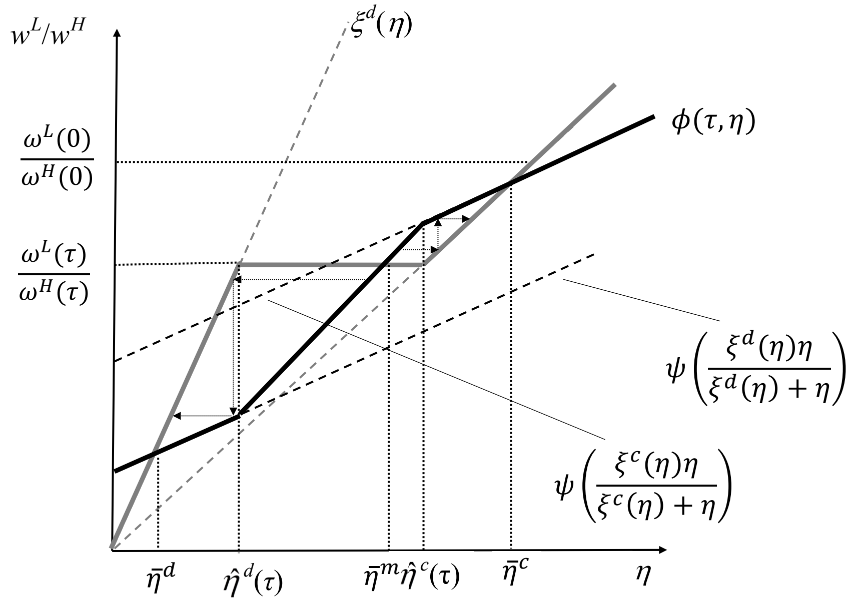

Figure 5

Proposition 7 *Imposing a tax on the dirty technology aimed at the switch to the clean technology may result in a temporary drop in the total output.*

As was noted above, since a switch to the clean technology will lead to accumulation of human capital, which, in turn will result in a higher total factor productivity and a higher growth rate. Thus, eventually imposing a tax on the dirty output will lead to a higher total output, though it may take some time for the clean technology to provide a higher total factor productivity than the dirty technology.

Also, if $\eta = \bar{\eta}^c$ is 0-SSE, Proposition 4 implies that even if the impact of human capital accumulation on the rate of growth of total factor productivity is weak, the convergence of the τ-equilibrium path guarantees that from some time onward the normalized total output will be higher than on any dirty equilibrium path.

It should be noted that if $\eta = \bar{\eta}^c$ is 0-SSE, then the tax rate that provides incentives to implement the clean technology can be decreasing and equal to zero as of some $t = T$.[7]

[7]Formally speaking, we defined an equilibrium path assuming constant tax rate on the dirty output. Nothing prevents us from generalizing these definitions to the case of a tax rate which is changing over time.

4.3 North-South Set-up

In this subsection we extend our model to an asymmetric two-country setting and we wish to study the consequences of human capital spillovers from one country, presumably more advanced, to the other. The question of knowledge and technology transfer from the developed to the developing countries has been a controversial topic, intensified by the discussion of the impacts of climate change. On the one hand, the technological gap between the so-called North and the so-called South made it obvious that the South's ability to mitigate and to adapt to climate change is severely hampered. During climate Conferences of the Parties, representatives of these countries have regularly expressed the view that the "rich" North should offer its help if it expects any cooperation on the climate policy. This help should, presumably, include a transfer of technological know-how allowing the South to adopt green production processes and be able to implement climate-change adaptation measures. On the other hand, such know-how is often protected by patent rights and is the property of individual firms who are reluctant to simply "give away" their technology. In this section we show that human capital spillovers from the developed to the developing economies have far-reaching consequences for clean technology adoption in the South and its growth convergence. Such a spillover may be generated through governmental educational programs, for example by allowing students from the developing economies to study in the universities of the advanced economies under the condition of subsequent return to the home country.

Suppose that the world consists of two countries, North and South, each described by the model of Section 2, except for the process of human capital accumulation in the South, which is described below. We shall assume that there is a positive human capital spillover from N to S, so that

$$h_t^S = \psi^S(H_{t-1}^S, H_{t-1}^N)$$

and that $\psi^S(H^S, H^N)$ is increasing in both H^S and H^N. Then the function ϕ^S can be written as $\phi^S(\tau, \eta^S, \eta^N)$.

In this case the transition of the North to the clean SSE and the accumulation of human capital in the North will shift the $\phi^S(\tau, \eta^S, \cdot)$ curve upwards. This shift will lead to widening of the domain of convergence to the clean SSE in the South.

Now assume that the production functions are of the form

$$Y_t^j = A_t F^j(H_t^j, L_t^j),\ j = c, d,$$

where the TFP A_t is common for the two sectors but different across countries:

$$A_t^N = G^N(H_{t-1}^N)A_{t-1}^N$$

and

$$A_t^S = G^S(H_{t-1}^S)B(A_{t-1}^N, A_{t-1}^S).$$

While the dynamics of TFP in the North are identical to those in Section 2, the dynamics of TFP in the South benefit from the TFP level in the North (again, through a positive spillover), as in Bretschger and Suphaphiphat (2014). In this case, human capital accumulation in the North indirectly benefits the South due to improvements in TFP. Consequently, the imposition of a carbon tax in the North and its effect on human capital formation causes a double positive effect in the South, i.e. by boosting human capital and by improving TFP growth. Then transition to the clean SSE in the North will increase the rate of growth in both the North and the South and the transition to the clean SSE in the South will help the South to catch up with North.

5 Conclusions

Policy debate over carbon taxation and environmental regulation often focuses on the short term costs and downplays the long-term benefits. In this paper we highlight an important and often overlooked dimension of carbon pricing related to the effect of transiting from dirty to clean technology on human capital formation, with its overall benefit for the TFP growth.

We have presented a dynamic model featuring the interactions among carbon pricing, technology transition and human capital accumulation. Our main results may be summarized as follows. Imposition of a carbon tax may induce a switch from dirty to clean production techniques and lead to the economy settling permanently in the "clean" steady-state equilibrium. Because the clean sector is assumed to be skill-intensive, this transition is accompanied by growth in the stock of human capital through its intergenerational spillover effect. Moreover, the interesting feature of the carbon policy is that it only needs to be temporary. This is because the clean SSE is stable, so that once the transition to it has been accomplished, there is no more need to maintain a positive tax rate, i.e. the tax rate may in fact be chosen to decline over time. Moreover, since the stock of human capital positively affects the rate of TFP growth (as is typically assumed in the growth literature), the carbon policy boosts economic growth by inducing human capital accumulation. Finally, in the presence of intercountry knowledge spillovers, i.e. when human capital accumulation in one country, say the North, produces positive effects on human capital formation in another country (say the South), for example through international educational student exchange programs, the latter enjoys a double positive effect. Not only its stock of human capital increases (without the South actually implementing any policy), but its TFP growth rises as well inducing the "catching-up" effect with the North.

It is common in the literature to assume that dirty production techniques are associated with degradation of the natural environment, which in turn creates a disutility for individual agents. We have side-stepped the analysis of the evolution of the natural environment, although such an analysis may be easily incorporated in our model. Clearly, if the economy is initially on the dirty path and no carbon policy is in place, the quality of the environment will decline over time. In this case we obtain the same outcome as, for example, in Proposition 2 of Acemoglu et al. (2012), namely that environmental disaster is unavoidable. If, however, an appropriate carbon tax is introduced and technology transition is set in motion, environmental disaster can be avoided. Note that, contrary to the findings of Acemoglu et al. (2012) in Propositions 3 and 6, the avoidance of a disaster in our setup does not depend either on the degree of substitutability between inputs or on the subsidization of the education sector. This is due to the fact that human capital accumulation in our model exhibits intergenerational positive spillover. When separately introducing the environment into the model it would also be straightforward to add a positive relationship between the state of the environment and human capital accumulation, as suggested by Zivin and Neidell (2013). This would unambiguously strengthen our conclusions about the growth effects in the transition to clean technologies.

Overall, we argue that carbon taxation brings about not only direct environmental benefits (e.g., in terms of reduced pollution and improved health) but also indirect positive effects on the economy through accumulation of the knowledge capital and increased total factor productivity.

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