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Working Paper 07/71
July 2007

Economics Working Paper Series

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The role of environmental and technology policies in the transition to a low-carbon energy industry

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Abstract: In a dynamic general equilibrium model we study the interplay between gradual and structural change in the transition to a low-carbon energy industry. We focus on the welfare-theoretic consequences of diverging social and private rates of time preference and a time-to-build feature in capital accumulation. Both features are particularly important in the transformation of energy systems. We show that only a combination of environmental and technology policies can achieve a socially optimal transition. We thus provide a new reason for environmental regulation to be complemented by technology policy such as a non-distortionary investment subsidy.

Keywords: environmental and technology policy, social vs. individual rates of time preference, time to build, gradual vs. structural technological change, energy industry

JEL classification: H23, Q48, H43

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* Valuable comments by Stefan Baumgärtner, Lucas Bretschger, Marco Lehmann-Waffenschmidt, Normann Lorenz, Till Requate, Maik Schneider, Marcel Thum and Christian Traeger are gratefully acknowledged. The usual disclaimer applies.

1 Introduction

How to accomplish the transition to a low-carbon energy industry in a socially optimal way is the subject of an ongoing debate. For instance, while the EU promotes emission reduction via environmental regulations that cap emissions (e.g. European Commission 2005), the US concentrate on technology policy to foster energy efficiency and progress in clean technologies (e.g. US Government 2002).[1] Typically, investments in the energy sector concern particularly long-lived and cost-intensive capital goods. They are also associated with particularly long construction times. Following the liberalisation of energy markets in most industrialized countries, such investment decisions are now mainly governed by private actors. At the same time, due to their environmental impact, they have long-term consequences for the society as a whole. Thus, apart from environmental preferences, time preferences on both the social and private levels are likely to play a key role in the transition to a low-emission energy industry. However, the long-standing debate on the correct determination and relationship of social and private time preference rates in economics has mostly been focussing on the optimal discounting of public projects (e.g. Groom et al. 2005, Lind et al. 1982, Luckert and Adamowicz 1993, Portney and Weyant 1999, Weitzman 2001). The welfare-theoretic implications for *private* investments have, thus far, only occasionally been alluded (rare exceptions include Arrow and Lind 1970, Baumol 1968, Grant and Quiggin 2003, Hirshleifer 1966).

We address this latter question in the specific context of energy sector transformation, where it is of a particular importance. We study the transition from an established polluting to a new clean energy technology. Our model combines two particular time-related features. First, we assume that the creation of new capital goods needs a positive time span σ. That is, there is a time lag σ between the costs of investment and the new capital goods becoming productive. Second, we assume the social rate of time preference to stay below the private. That means that individual actors are more impatient to consume than society as a whole. In addition, we consider two kinds of technological change, gradual and structural, which correspond to two competing emission reduction options. By *gradual* technological change, we understand the gradual refinement of the existing technology via an end-of-pipe abatement technology. By *structural* technological change, we mean the introduction of a new clean technology. We assume that the new technology is only to be produced and that it may replace the established one. We show that the two externalities the model integrates, the emission externality as well as the split of social and private time preference rates, create, in a mutually reinforcing way, less favorable circumstances for the introduction of the new and the replacement of the old energy technology compared to the social optimum. The time lag in capital accumulation amplifies the distortion induced by the diverging time preference rates. We show how the two distortions can be internalized by a combination of environmental and technology policies.

Our paper contributes to the wide-spanned literature on induced technological change

[1] This impasse between the EU and the US is not only reflected in the US refusal to ratify the Kyoto protocol, but also an important issue in the recent political debate about international climate change mitigation agreements for the post-Kyoto era.

and the environment. In this literature, the intertemporal nature of the climate change problem is mostly addressed either in endogenous growth or integrated assessment models. Top-down approaches study induced technological change by applying one representative aggregated production technology, which becomes more efficient and/or less polluting by technological change (e.g. Goulder and Mathai 2000, Müller-Fürstenberger and Stephan forthcoming, Nordhaus 2002, Newell et al. 1999). In bottom-up approaches, induced technological change also allows for structural change between competing technologies (e.g. Gerlagh and Van der Zwaan 2003, Goulder and Schneider 1999, Van der Zwaan et al. 2002). They all have in common that they model technological change endogenously as a gradual improvement resulting either from R&D investments or learning by doing. Thus far, this literature has been focussing on positive spillovers to other firms from the innovation process or dynamic increasing returns stemming from learning by using, learning by doing or network externalities typically related to the diffusion of new technologies as sources of market failure inducing technology policy (Jaffe et al. 2005). We neglect these further components of long-run technological change and rather adopt, as in Winkler (forthcoming), a medium-term perspective with qualitatively invariable technologies, in order to concentrate on the welfare-theoretic consequences of the split of social and private time preference rates and the time-to-build feature.

Although derived from a stylized theoretical model, our results have direct policy implications. First, we provide a new reason why environmental regulation should be complemented by technology policy. Second, our results give new theoretical support for a *non-distortionary* subsidizing of new less polluting energy technologies. Third, our analysis can substantiate Porter and van der Linde's (1995) claim that "well-designed" environmental regulations exhibit a double dividend providing both for less pollution and a higher competitiveness.

The paper is organized as follows. Section 2 introduces the model and discusses the assumption of the split of social and individual rates of time preference. In sections 3 and 4, the intertemporal optimization problems are solved and conditions of investment and replacement derived for the cases of the social optimum and an unregulated competitive market economy, respectively. Section 5 shows how the two distortions, stemming from the emissions and the split of social and individual rates of time preference, can be internalized via environmental and technology regulation. We discuss our model assumptions and policy implications in section 6. Section 7 concludes.

2 The model

Consider an economy composed of two vertically integrated sectors, the energy sector and the investment sector. Labor constitutes the only primary input, which by assumption is fixed to unity at all times t.

The energy sector comprises two technologies, an *established* and a *new* one. The established technology is assumed to be fully set up at the beginning of the planning horizon. As a consequence, we do not explicitly consider capital for the established technology, but include the costs of employing and maintaining the capital stock into the labor costs which are normalized to 1. The established technology generates one unit of energy x for every unit of labor l_1 employed. In addition, each unit of energy produced gives rise to one unit of an unwanted and harmful joint output j:

$$x_1(t) = l_1(t) = j(t) \ . \tag{1}$$

Abatement effort a per unit of output (partially) disarms the joint output. The function G denotes the fraction of the joint output j which is disarmed by abatement. G is assumed to be twice continuously differentiable, satisfying $G(0) = 0$, $G' > 0$, $G'' < 0$ and $\lim_{a\to\infty} G(a) = 1$. Moreover, the Inada conditions $\lim_{a\to 0} G'(a) = \infty$, $\lim_{a\to\infty} G'(a) = 0$ are imposed ensuring that the abatement effort a along the optimal path is strictly positive and finite as long as l_1 is positive. Then, net emissions e equal the amount of joint output j minus abatement:

$$e(t) = x_1(t)\big(1 - G(a(t))\big) \ . \tag{2}$$

The new technology employs λ units of labor together with κ units of the capital good k to produce one unit of energy:

$$x_2(t) = \min\left[\frac{l_2(t)}{\lambda}, \frac{k(t)}{\kappa}\right] \ . \tag{3}$$

Assuming an efficient labor allocation among the three production processes in the two sectors, i.e. $1 = (1 + a(t))l_1(t) + l_2(t) + i(t)\ \forall t$, an initial capital stock of $k(0) = 0$, and intertemporal welfare as defined in equations (6) and (7) below, full employment of the capital stock can be shown to be *efficient* (Winkler 2005), and equation (3) yields $x_2(t) = \frac{l_2(t)}{\lambda} = \frac{k(t)}{\kappa}$. Without loss of generality the new technology does not produce any unwanted joint outputs. As energy is supposed to be homogeneous, total energy production x equals:

$$x(t) = x_1(t) + x_2(t) \ . \tag{4}$$

The *investment* sector employs one unit of labor to produce one unit of the capital good. We assume that the creation of new capital goods needs a positive time span σ. That is, there is a time-lag σ between the costs of investment i and the emergence of productive capital k. The intuition behind this assumption is twofold. On the one hand, power plants are not built in a day but need *substantial time* for creation.[2] On the other hand, the time-lag σ can also be identified with the time required for the R&D of a new technology. In addition, the capital stock k deteriorates at the constant and exogenously given rate γ, implying the following equation of motion:

$$\frac{dk(t)}{dt} = i(t - \sigma) - \gamma k(t) \ , \quad \gamma > 0 \ . \tag{5}$$

[2] In general, the time span σ strongly depends on the type of plant produced. While a new nuclear power plant may take five to seven years to be built, a gas co-generation plant is set up in a year or two.

Due to the time-lag σ the equation of motion for the capital stock (5) constitutes a *retarded differential-difference* equation. Thus, variations of the capital stock k do not only depend on parameters evaluated at time t but also on parameters evaluated at the earlier time $t - \sigma$.

To close the model we consider a representative consumer who derives instantaneous utility from energy consumption and disutility from net emissions.[3] Like Arrow and Kurz (1970: 116) we assume that the representative consumer's private rate of time preference differs from the social. That is, the representative consumer applies different *intertemporal* weights between welfare today and welfare tomorrow compared to a social planner maximizing social welfare. For the sake of simplicity, we consider instantaneous welfare to be additively separable in energy consumption x and net emissions e. As a consequence, the representative consumer (privately) maximizes

$$W_p = \int_0^\infty \big[U(x(t)) - D(e(t))\big] \exp[-\rho_p t] \, dt \ , \tag{6}$$

whereas, at the same time, the social planner maximizes

$$W = \int_0^\infty \big[U(x(t)) - D(e(t))\big] \exp[-\rho t] \, dt \ , \tag{7}$$

where U and D are twice differentiable functions with $U' > 0$, $U'' < 0$, and $\lim_{x \to 0} U' = \infty$ and $D'(0) \geq 0$, $D' > 0$ for any positive amount of emissions e, and $D'' > 0$. We assume that the private rate of time preference ρ_p is higher than the socially efficient rate ρ, i.e. $\rho_p > \rho$, which is in line with empirical findings (e.g. Lazaro et al. 2001).

To further motivate our assumption we briefly introduce two reasons why private and social rates of time preference may differ. The first refers to the well established fact in finance that there exists a (negative) spread between government and private security rates of any maturity.[4] Considering a framework where problems of adverse selection prevent risk-averse individuals from insuring against systematic labour income risk, Grant and Quiggin (2003) show that, for prudent behavior in the sense of Kimball (1990) (i.e. marginal utility is strictly convex), the incapacity to fully pool idiosyncratic risk leads to an enhanced risk premium for equity. The second reason has been advanced by Gollier (2002). His aim is to determine the socially optimal discount rate for public projects the time horizons of which extend far beyond the longest maturity of any security available. He shows, again for the case of prudence, that uncertain growth leads to a social discount rate that is smaller than in the case of certain growth and, moreover, declines over time.

The importance of both arguments for the present analysis is obvious. In liberalized markets, (private) utilities rely upon the private financial market to finance investments

[3] Obviously, CO_2 is a stock and not a flow pollutant. However, assuming that the negative externality on utility is caused by the emissions and not the global stock simplifies further calculations without impacting on our qualitative results (for further discussion, see section 6).

[4] The issue has been discussed in a broad literature in both economics and finance particularly following the statement of the so-called equity-premium and risk-free rate puzzles (e.g. Mehra and Prescott 1985, Weil 1989).

in new technologies. Any distortion of it affects private investment. The factual inability of financial markets to reflect and to insure long-term risks associated with investment projects, such as those related to anthropogenic climate change, constitutes a case for welfare-enhancing government intervention. In view of the ongoing discussion with respect to causes and policy treatments we omit, however, an endogenous explanation of the split of time preference rates and rather focus on the implications of this assumption.

3 Social optimum

We now derive the optimal plan for the development of the model economy. As outlined in section 2, social welfare is assumed to be given by equation (7). Thus, the social planner solves the following maximization problem:

$$\max_{a(t),i(t)} W = \int_0^\infty \big[U(x(t)) - D(e(t))\big] \exp[-\rho t]\, dt \ , \tag{8a}$$

subject to

$$\begin{aligned}
x(t) &= \frac{1 - \frac{\lambda}{\kappa}k(t) - i(t)}{1 + a(t)} + \frac{1}{\kappa}k(t) \ , && \text{(8b)}\\
e(t) &= \Big(1 - G(a(t))\Big)\left[\frac{1 - \frac{\lambda}{\kappa}k(t) - i(t)}{1 + a(t)}\right] \ , && \text{(8c)}\\
\frac{dk(t)}{dt} &= i(t-\sigma) - \gamma k(t) \ , && \text{(8d)}\\
i(t) &\geq 0 \ , && \text{(8e)}\\
l_1(t) &\geq 0 \ , && \text{(8f)}\\
k(0) &= 0 \ , && \text{(8g)}\\
i(t) &= \xi(t) \ = \ 0, \quad t \in [-\sigma, 0) \ . && \text{(8h)}
\end{aligned}$$

For the dynamics of the model economy it is important that, due to the linearity of the production techniques, two *corner solutions* can occur along the optimal development path. Either, it can be optimal to only use the established technology at all times, which corresponds to $i(t) = 0 \ \forall t$. Or, if investment in the new technology is optimal (i.e. $i(t) > 0 \ \forall t$), the new technology may eventually fully replace the established one and thus $l_1(t) = 0 \ \forall t \geq t'$. As a consequence, we have to explicitly check these two corner solutions, apart from the inner solution, in order to characterize the complete dynamics of the model economy.

3.1 Necessary and sufficient conditions for the social optimum

To solve the optimization problem (8), we apply the generalized maximum principle derived in El-Hodiri et al. (1972) for time-lagged optimal control problems. One obtains the following present-value Hamiltonian $\mathcal{H}$:

$$\begin{aligned}
\mathcal{H} &= \big[U(x(t)) - D(e(t))\big]\exp[-\rho t] \\
&+ q_x(t)\left[\frac{1-\frac{\lambda}{\kappa}k(t)-i(t)}{1+a(t)} + \frac{1}{\kappa}k(t) - x(t)\right] \\
&+ q_e(t)\left[\Big(1-G(a(t))\Big)\frac{1-\frac{\lambda}{\kappa}k(t)-i(t)}{1+a(t)} - e(t)\right] \\
&+ q_k(t+\sigma)i(t) - q_k(t)\gamma k(t) \\
&+ q_i(t)i(t) \\
&+ q_{l_1}(t)\frac{1-\frac{\lambda}{\kappa}k(t)-i(t)}{1+a(t)} \ ,
\end{aligned} \tag{9}$$

where q_k denotes the costate variable or shadow price of the capital stock k, and q_x, q_e, q_i and q_{l_1} denote the Kuhn-Tucker parameters for the (in)equality conditions (8b), (8c), (8e) and (8f). Assuming the Hamiltonian $\mathcal{H}$ to be continuously differentiable with respect to the control variables a and i, the following necessary conditions hold for an optimal solution:

$$q_x(t) = U'(x(t))\exp[-\rho t] \ , \tag{10a}$$

$$q_e(t) = -D'(e(t))\exp[-\rho t] \ , \tag{10b}$$

$$\frac{q_x(t)l_1(t)}{1+a(t)} = -q_e(t)l_1(t)\left[G'(a(t)) + \frac{1-G(a(t))}{1+a(t)}\right] + \frac{q_{l_1}(t)l_1(t)}{1+a(t)} \ , \tag{10c}$$

$$\frac{q_x(t)}{1+a(t)} = -q_e(t)\left[\frac{1-G(a(t))}{1+a(t)}\right] + q_k(t+\sigma) + q_i(t) - \frac{q_{l_1}(t)}{1+a(t)} \ , \tag{10d}$$

$$\frac{dq_k(t)}{dt} = q_e(t)\frac{\lambda(1-G(a(t))}{\kappa(1+a(t))} - q_x(t)\frac{1+a(t)-\lambda}{\kappa(1+a(t))} + q_k(t)\gamma + \frac{q_{l_1}(t)\lambda}{\kappa(1+a(t))} \ , \tag{10e}$$

$$q_i(t) \geq 0 \ , \quad q_i(t)i(t) = 0 \ , \tag{10f}$$

$$q_{l_1}(t) \geq 0 \ , \quad q_{l_1}(t)l_1(t) = 0 \ . \tag{10g}$$

As the maximized Hamiltonian is concave (cf. Appendix A.1), the necessary conditions (10a)–(10g) are also sufficient if, in addition, the following transversality condition holds:

$$\lim_{t\to\infty} q_k(t)k(t) = 0 \ . \tag{10h}$$

Due to the *strict* concavity of the maximized Hamiltonian, the optimal solution is also unique.

Conditions (10a) and (10b) state that along the optimal path the shadow price of energy equals the marginal utility of energy and the shadow price of net emissions equals the marginal disutility of net emissions. From condition (10g) we know that $q_{l_1}l_1 = 0 \,\forall\, t$. Hence, the last term in condition (10c) equals 0 and, as long as $l_1(t) > 0$, we achieve by inserting conditions (10a) and (10b):

$$U'(x(t)) = D'(e(t))\left[G'(a(t))\left(1+a(t)\right) + 1 - G(a(t))\right] \ . \tag{11}$$

This condition expresses that along the optimal path (and as long as condition (8f) is not binding) the utility (in current values) of an additional marginal unit of energy equals the disutility (in current values) of the emissions that it induces. Along the optimal path this equation determines the optimal value of the abatement effort a per unit of output x_1. If inequality (8f) is binding and thus l_1 equals 0, condition (10c) reduces to the truism $0 = 0$. It is obvious, however, that if the established technique is not used at all, the optimal abatement effort $a = 0$ as no emissions have to be abated.

As noted above, the optimal system dynamics of the optimization problem (8) splits into three cases, an interior solution and two corner solutions. In Appendix A.2 we derive the system of functional differential equations for the system dynamics and show that each case exhibits a (different) stationary state. In particular, the stationary state of the interior solution represents a saddle point, i.e. for all sets of initial conditions there exists a unique optimal path which converges towards the stationary state.

We first restrict our attention to the case of an *interior solution*, i.e. $q_i(t) = q_{l_1}(t) = 0$. Together with transversality condition (10h), and inserting conditions (10a) and (10b), condition (10e) can be unambiguously solved:

$$q_k(t) = \int_t^\infty \frac{U'(x(s))(1+a(s)-\lambda) + D'(e(s))\lambda\big(1-G(a(s))\big)}{\kappa(1+a(s))} \exp[-\gamma(s-t)-\rho s]ds \; . \quad (12)$$

Thus, along the optimal path the shadow price for the capital stock equals the net present value of all future welfare gains of one additional marginal unit of the capital good. As capital goods are long-lived, they contribute over the whole time horizon (increasingly less though due to deterioration). The fraction under the integral equals the marginal instantaneous welfare gain of an additional unit of capital, which comprises two components. The first is the direct welfare gain due to the energy produced. It is positive if the new technology needs less labor input per unit of output than the established one, i.e. $\lambda < 1 + a$. The second term is always positive and denotes the welfare gain due to emissions abated by switching from the established to the new production technique.

Inserting conditions (10a) and (10b) in equation (10d) yields:

$$\frac{U'(x(t)) + D'(e(t))\big(1 - G(a(t))\big)}{1 + a(t)} \exp[-\rho t] = q_k(t + \sigma) \quad (13)$$

The equation states that along the optimal path the present value of the welfare loss by investing in one marginal unit of new capital, which is given by the present value welfare gain of the alternative use of one marginal unit of labor in the established production technique (left-hand side), equals the net present value of the sum of all future welfare gains by using the new capital good in production. As the investment needs the time span σ to become productive capital, the sum of all future welfare gains of an investment at time t is given by the shadow price of capital at time $t+\sigma$, $q_k(t+\sigma)$. Note that equation (13) implies that q_k is always positive along the optimal path. As a consequence, the second term of the fraction in equation (12) outweighs the first.

3.2 Conditions for investment and replacement

However, so far it is not clear to which of the three possible stationary states the system will tend. In the following, we derive conditions for the exogenous parameters identifying which of the three possible cases for the system dynamics applies. In fact, these conditions determine whether there is any investment in the new technology, and if so, whether the established technology is eventually fully replaced by the new one. We start with the investment condition.

In order to derive a condition which identifies whether investment is optimal, we assume the economy to stay in the no investment corner solution and derive a condition for which the corner solution violates the necessary and sufficient condition for an optimal solution. The following proposition states the result.

Proposition 1 (Investment condition in the social optimum)
Given the optimization problem (8), the new technology is innovated, i.e. $i(t) > 0$*, if and only if the following condition holds:*

$$1 + a^0 + \frac{1 - G(a^0)}{G'(a^0)} > \lambda + \kappa(\gamma + \rho)\exp[\rho\sigma] \ , \tag{14}$$

where a^0 *is determined by the unique solution of the implicit equation:*

$$\frac{U'(1 - a^0)}{D'\big((1 - a^0)(1 - G(a^0))\big)} = G'(a^0)(1 + a^0) + 1 - G(a^0) \ . \tag{15}$$

Proof: See Appendix A.4.

Condition (14) for the investment in the new technology has an intuitive economic interpretation. In the corner solution without investment the left-hand side corresponds to the unit costs of energy production of the established technology $UC^0_{T_1}$, the right-hand side to the unit costs of energy production of the new technology $UC^0_{T_2}$. Thus, condition (14) states that for the new technology to be innovated its unit costs of production have to be below those of the established technology, i.e. $UC^0_{T_2} < UC^0_{T_1}$.

The unit costs of production of the first technology comprise three components, the 'pure' labor costs per unit of energy production, the labor costs for abatement per unit, and the social costs of unit emissions in terms of labor. The unit costs of production of the non-polluting new technology comprise, apart from the 'pure' labor costs, the costs for building up and maintaining the necessary capital good in terms of labor. Obviously, the capital costs per unit of output depend positively on the capital intensity κ, the dynamic characteristics γ and σ of the capital good production, as well as on the time preference rate ρ. In particular, the longer the time-lag σ and the higher the rate of time preference ρ the higher are the unit costs of energy of the new technology.[5]

Despite the infinite time horizon and the linearity of the two production techniques, condition (14) does not guarantee full replacement of the established technology by

[5] In general, the unit costs of energy during transition periods are not constant, as consumption and emission levels change over time. Thus, they are not necessarily given by $UC^0_{T_1}$ and $UC^0_{T_2}$.

the new technology in the long run. In the following, we deduce conditions for which complete or partial replacement occur in the long run. In formal terms, full replacement of the established by the new production technique is given by the full replacement corner solution $l_1(t) = 0$. The line of argument to derive a condition for full replacement is similar to the inference of proposition 1. We investigate under which conditions a full replacement stationary state, in which all labor is used to employ and maintain the fully developed new technology, is consistent with the necessary and sufficient conditions for an optimal solution as given by equations (10a)–(10h). The following proposition states the result.

Proposition 2 (Full replacement condition in the social optimum)
Given the optimization problem (8) and assuming $U'(x^\infty) - D'(0) \neq 0$, full replacement of the established technology by the new one in the long-run stationary state is consistent with the necessary and sufficient conditions for a social optimum, if and only if the following condition holds:

$$1 + \frac{D'(0)}{U'(x^\infty) - D'(0)} \geq \lambda + \kappa(\gamma + \rho) \exp[\rho\sigma] \ , \tag{16}$$

where x^∞ is given by $x^\infty = \frac{1}{\lambda + \kappa\gamma}$.

Proof: See Appendix A.5.

The economic interpretation of the full replacement condition (16) is analogous to the one of the investment condition (14). Full replacement can only take place if the costs per unit of output of the new technology in the full replacement stationary state $UC_{T_2}^\infty$ (right-hand side) are smaller than or equal to the costs of the established technology $UC_{T_1}^\infty$ (left-hand side). As there are no emissions, there are no labor costs for abatement effort in the full replacement stationary state. Thus, the unit costs of the established technology only consist of the 'pure' labor costs plus the social costs, which stem from emissions. In the common case that the first marginal unit of emissions does not induce any environmental damage, i. e. $D'(0) = 0$ (e.g. D is a power function), the unit costs of the established technology reduce to the 'pure' labor costs of production. Note that condition (16) is not well defined, if $\lim_{x \to x^\infty} U'(x) = D'(0)$ holds. However, also in this special case full replacement will occur if, in addition, condition (14) holds because the welfare gain of an additional unit of labor assigned to the old technology vanishes while the shadow price of capital, which is the net present value of all future welfare gains of an additional unit of capital, remains positive. The unit costs of the new technology are identical in both situations as they do not depend on the level of emissions and its implied disutility.[6]

For full replacement to occur conditions (14) and (16) must hold at the same time. Thus, a straightforward corollary from propositions 1 and 2 is that *partial* replacement of the established by the new technology (i.e. the long-run stationary state is an interior solution) takes place, if condition (14) holds but condition (16) is violated.

[6] In fact, the unit costs of the new technology are the same among *all* possible stationary states.

Corollary 1 (Partial replacement condition in the social optimum)
Given the optimization problem (8) and that $U'(x^\infty) - D'(0) \neq 0$, partial replacement of the established technology by the new one is optimal in the long-run stationary state, i.e. the long-run stationary state is an interior solution, if and only if the following condition holds:

$$1 + a^0 + \frac{1 - G(a^0)}{G'(a^0)} > \lambda + \kappa(\gamma + \rho)\exp[\rho\sigma] > 1 + \frac{D'(0)}{U'(x^\infty) - D'(0)} \ , \tag{17}$$

where $x^\infty = \frac{1}{\lambda + \kappa\gamma}$ and a^0 is given by the unique solution of the implicit equation (15).

In sum, investment is never optimal if the labor costs per unit of output of the new technology, $UC_{T_2} = UC^0_{T_2} = UC^\infty_{T_2}$, are higher than the labor costs per unit of output of the established technology in the no investment corner solution, $UC^0_{T_1}$. If investment is optimal, i.e. $UC_{T_2} < UC^0_{T_1}$, full replacement in the long-run stationary state is optimal if, in addition, $UC_{T_2} \leq UC^\infty_{T_1}$ holds. Otherwise, i.e. $UC^\infty_{T_1} < UC_{T_2} < UC^0_{T_1}$, the new technology will partly replace the established technology in the optimal long-run stationary state.

4 Unregulated competitive market equilibrium

We now assume that the allocation of the model economy is determined by the decisions of individual actors in an unregulated market regime. We assume competitive markets for labor, capital and energy, in which one representative household and two representative firms interact. We suppose that all markets are cleared at all times, and thus supply equals demand. As emissions are free, though negatively valued by the household, the firms do not account for them in their market decisions. We consider a representative consumer who exhibits different preferences in an individual compared to a social decision context. More precisely, we assume that in the market regime the preferences of the representative consumer are given by equation (6), which differs from equation (7) by a *higher* rate of time preference ρ_p.

Analogously to the analysis of the social optimum we derive conditions for investment in the new technology and for the replacement of the established technology in the long-run stationary state. We study how the emission externality and the split of time preference rates affect these conditions.

4.1 The household's market decisions

The household is assumed to own the two firms and the total labor and capital endowment of the economy. Thus, the household chooses between selling labor to the firms at the market price of labor w or to invest labor in the accumulation of capital k, which the household rents to the firms at the market price of capital r. In addition, the household buys energy x at the market price of energy p. As the household cannot incur debts, the following budget constraint has to hold for all times t:

$$p(t)x(t) = w(t)\big(1 - i(t)\big) + r(t)k(t) + \pi_1(t) + \pi_2(t) \ , \tag{18}$$

where π_1 and π_2 denote the profits of firm 1 and 2. In addition, capital can be accumulated according to equation (5).

The household is assumed to maximize its intertemporal welfare (6), i.e. the household solves the following maximization problem:

$$\max_{i(t)} \int_0^\infty \big[U(x(t)) - D(e(t))\big] \exp[-\rho_p t]\, dt \ , \tag{19a}$$

subject to

$$\begin{aligned}
p(t)x(t) &= w(t)\big(1 - i(t)\big) + r(t)k(t) + \pi_1(t) + \pi_2(t) \ , && (19\text{b})\\
\frac{dk(t)}{dt} &= i(t-\sigma) - \gamma k(t) \ , && (19\text{c})\\
i(t) &\geq 0 \ , && (19\text{d})\\
k(0) &= 0 \ , && (19\text{e})\\
i(t) &= \xi(t) \ = \ 0, \quad t \in [-\sigma, 0) \ . && (19\text{f})
\end{aligned}$$

Thus, the present value Hamiltonian $\mathcal{H}^H$ reads:

$$\begin{aligned}
\mathcal{H}^H \ = \ & \big[U(x(t)) - D(e(t))\big] \exp[-\rho_p t] && (20\text{a})\\
& + q_b(t) \big[w(t)\big(1 - i(t)\big) + r(t)k(t) - p(t)x(t)\big] && (20\text{b})\\
& + q_k(t+\sigma)i(t) - q_k(t)\gamma k(t) && (20\text{c})\\
& + q_i(t)i(t) \ , && (20\text{d})
\end{aligned}$$

where q_k denotes the costate variable or shadow price of the capital stock k, and q_b and q_i denote the Kuhn-Tucker parameters for the (in)equality conditions (19b)and (19d). The strict concavity of the Hamiltonian $\mathcal{H}^H$ can be shown following a similar line of argument as in Appendix A.1 and ensures a unique solution.

Assuming that the Hamiltonian $\mathcal{H}^H$ is continuously differentiable with respect to the control variable i the following necessary conditions hold for an optimal solution:

$$\begin{aligned}
q_b(t)p(t) &= U'(x(t)) \exp[-\rho_p t] \ , && (21\text{a})\\
q_b(t)w(t) &= q_k(t+\sigma) + q_i(t) \ , && (21\text{b})\\
-\frac{dq_k(t)}{dt} &= q_b(t)r(t) - q_k(t)\gamma \ , && (21\text{c})\\
q_i(t) &\geq 0 \ , \quad q_i(t)i(t) \ = \ 0 \ . && (21\text{d})
\end{aligned}$$

Due to the concavity of the Hamiltonian, the necessary conditions (21a)–(21d) are also sufficient if in addition a transversality condition analogous to condition (10h) holds. Together with condition (21a), condition (21c) can be unambiguously solved to yield:

$$q_k(t) = \exp[\gamma t] \int_t^\infty q_b(s)r(s) \exp[-\gamma s] ds \ . \tag{22}$$

4.2 The firms' market decisions

Taking prices as given, the firms maximize their profits in the competitive market equilibrium. Firm 1 produces energy according to the first production technology described by equations (1) and (8c). Thus, the profit π_1 at time t is given by:

$$\pi_1(t) = p(t)l_1(t) - w(t)\big(1 + a(t)\big)l_1(t) \ . \tag{23}$$

Firm 1 chooses l_1 and a such as to maximize the net present value of all future profits which is equivalent to maximize the profit π_1 at all times t. As the negative externality of emissions is not accounted for in the unregulated market economy, abatement effort a is a pure cost to the firm, and thus $a(t) = 0$ is a necessary condition for a profit maximum. As π_1 is linear in l_1, π_1 is non-negative for any $l_1 > 0$ as long as output prices exceed input prices. Hence, the labor demand of firm 1 is given by the following correspondence:

$$l_1(t) \begin{cases} = \ \infty & , \text{ if } \ p(t) > w(t) \\ \in \ [0, \infty) & , \text{ if } \ p(t) = w(t) \\ = \ 0 & , \text{ if } \ p(t) < w(t) \end{cases} \ . \tag{24}$$

Firm 2 produces energy according to the second production technology described by equation (3). Thus, the profit π_2 at time t equals:

$$\pi_2(t) = \frac{1}{\kappa}p(t)k(t) - \frac{\lambda}{\kappa}w(t)k(t) - r(t)k(t) \ , \tag{25}$$

which is a linear function of k. As a consequence, the profit π_2 is non-negative for any $k > 0$ as long as the value of outputs exceeds the value of inputs. Analogously to firm 1, firm 2 demands as much capital as possible together with $\frac{\lambda}{\kappa}k$ units of labor, if the value of the output exceeds the value of the inputs. Thus, the demand of firm 2 is given by the following correspondence:

$$k(t) \begin{cases} = \ \infty \ \wedge \ l_2(t) = \frac{\lambda}{\kappa}k(t) = \infty & , \text{ if } \ p(t) > \lambda w(t) + \kappa r(t) \\ \in \ [0, \infty) \ \wedge \ l_2(t) = \frac{\lambda}{\kappa}k(t) & , \text{ if } \ p(t) = \lambda w(t) + \kappa r(t) \\ = \ 0 \ \wedge \ l_2(t) = 0 & , \text{ if } \ p(t) < \lambda w(t) + \kappa r(t) \end{cases} \ . \tag{26}$$

4.3 Necessary and sufficient condition for the market equilibrium

In the market equilibrium all markets clear and thus supply equals demand. As in the social optimum, the market solution may exhibit two corner solutions, in whichthe household never invests in capital or the total labor endowment is used to employ and maintain the capital stock. In the former case firm 2 is unable to operate, while in the latter case firm 1 is driven out of the market.

First, we analyze the interior market equilibrium where both firms operate. From the demand correspondences (24) and (26) of firm 1 and firm 2 we know that for positive and finite levels of l_1, l_2 and k the following conditions hold:

$$\frac{w(t)}{p(t)} = 1 \ , \quad \frac{r(t)}{p(t)} = \frac{1}{\kappa}\left(1 + \lambda\frac{w(t)}{p(t)}\right) = \frac{1-\lambda}{\kappa} \ . \tag{27}$$

Solving equation (21a) for q_b and taking into account conditions (27), we achieve for the shadow price of capital q_k

$$q_k(t) = \frac{1-\lambda}{\kappa} \exp[\gamma t] \int_t^\infty U'(x(s)) \exp[-(\gamma + \rho_p)s] \, ds \ , \tag{28}$$

and the following necessary and sufficient condition for an interior market equilibrium:

$$U'(x(t)) \exp[-\rho_p t] = q_k(t+\sigma) \ . \tag{29}$$

Analogously to the corresponding condition (13) in the social optimum, equation (29) states that along the optimal path the present value of the household's welfare loss by investing in one marginal unit of new capital, given by the present value welfare gain of the alternative use of one marginal unit of labor in the established production technique (left-hand side), equals the net present value of the sum of all future welfare gains by using the new capital good in production. Both costs and benefits of investment are smaller in the market equilibrium compared to the social optimum. However, in order to decide how the unregulated market regime influences the conditions of investment and replacement we have to check them explicitly.

4.4 Conditions for investment and replacement

Again, we assume the economy to stay in the no investment corner solution in order to derive the investment condition. Given the stationary state with no investment in capital at all times, we derive a condition on the exogenous parameters for which the corner solution violates the necessary and sufficient condition (29) for an unregulated market solution. The following proposition states this condition.

Proposition 3 (Investment condition in the competitive market equilibrium) *Given the optimization problem (19) of the representative household and the profit functions (23) and (25) of firm 1 and firm 2, the new technology is innovated, i.e.* $i(t) > 0$, *if and only if the following condition holds:*

$$1 > \lambda + \kappa(\gamma + \rho_p) \exp[\rho_p \sigma] \ . \tag{30}$$

Proof: See Appendix A.6.

Condition (30) displays the unit costs of energy production of the established and the new technology in the competitive market equilibrium. Again,the new technology has to display lower unit costs of production than the established technology in order to be innovated. As the social costs of pollution are not accounted for in the unregulated market regime, firm 1 has no incentive to abate. The unit costs of energy of the established technology reduce to the 'pure' costs of production, and are thus *lower* than socially optimal. The unit costs of energy of the new technology display the same composition as in the social optimum. As they now depend on $\rho_p > \rho$, they *exceed* the socially optimal unit costs of energy of the new technology. Thus, in the unregulated market equilibrium the new technology is disadvantaged in a twofold manner compared to the the social optimum.

As there is no abatement, investment in the new technology according to condition (30) always implies the full replacement of the initially established technology in the long run. The following proposition states these results.

Proposition 4 (Full replacement in the competitive market equilibrium) *Given the optimization problem (19) of the representative household, the profit functions (23) and (25) of firm 1 and firm 2, full replacement of the established technology by the new one in the long-run stationary state is consistent with the necessary and sufficient conditions for a competitive market equilibrium, if and only if the following condition holds:*

$$1 \geq \lambda + \kappa(\gamma + \rho_p) \exp[\rho_p \sigma] \ . \tag{31}$$

In particular, this implies that partial replacement of the established technology by the new one cannot occur in the unregulated market regime.

Proof: See Appendix A.7.

At first sight it might be puzzling that condition (30) is a strict inequality while condition (31) also allows for the equality sign to hold. Condition (31) states the requirements for a full replacement stationary state to be consistent with the necessary and sufficient conditions for a market equilibrium. However, from the strict inequality (30) we know that starting with a vanishing capital stock $k(0) = 0$ there is no investment at all times, if the equality sign in (31) holds. Nevertheless, in the hypothetical situation that the economy would already start with the full replacement capital stock $k^\infty = \frac{\kappa}{\lambda + \kappa\gamma}$ and that, in addition, condition (31) holds with equality, the economy would stay in the full replacement market equilibrium forever.

In sum, in the unregulated market economy the new technology has to exhibit lower costs per unit of output than the '*pure*' labor costs of the established technology to be innovated. This holds as the social costs of emissions which are an inevitable joint output of the old production technique are not accounted for in the market equilibrium. Moreover, the unit costs of the new technology are higher in the unregulated market equilibrium as compared to the social optimum. This difference is caused by the costs of waiting until the new capital good becomes productive, which increases because of the higher rate of time preference ρ_p of individual actors as compared to the social rate of time preference ρ. Thus, in a mutually reinforcing way the emission externality and the split of the rates of time preference imply that the new technology might not be innovated in the competitive market equilibrium, although innovation would be socially optimal.

5 Competitive market equilibrium with emission tax and investment subsidy

Now we consider how the social optimum can be implemented in a decentralized market regime. In general, two independent instruments are needed to implement the social optimum corresponding to the two externalities arising in the model. In fact, we study the introduction of an emission tax τ_e to internalize the emission externality, and of an investment subsidy τ_i to internalize the second distortion associated with the split of time preference rates. We assume the emission tax to be a tax per unit of emissions, collected directly from firm 1, and the investment subsidy to be a subsidy per unit of investment, paid directly to the household.

5.1 The household's and firms' market decisions under regulation

The emission tax and the investment subsidy alter the profit function of firm 1 and the household's maximization problem. Thus, we have to reconsider the corresponding decisions in a regulated market regime. Given a per unit tax τ_e per unit of emissions, the profit function of firm 1 reads:

$$\pi_1(t) = p(t)l_1(t) - w(t)(1 + a(t))l_1(t) - \tau_e(t)\big(1 - G(a(t))\big)l_1(t) \ . \tag{32}$$

Firm 1 chooses both labor l_1 and abatement effort a such as to maximize the net present value of all future profits, which is equivalent to maximizing the profit π_1 at all times t. A necessary condition for profit maximization is

$$\frac{\partial \pi_1(t)}{\partial a(t)} = -l_1(t)w(t) + \tau_e(t)G'(a(t))l_1(t) = 0 \ , \tag{33}$$

which is an implicit equation for the unique optimal abatement effort $a^\star(t)$ as long as $l_1(t) > 0$. However, if $l_1(t) = 0$, the optimal abatement effort $a^\star(t) = 0$ as no emissions have to be abated. Again, the profit function $\pi_1(t)$ is linear in the labor demand $l_1(t)$. Thus, the demand for $l_1(t)$ is given by the following correspondence:

$$l_1(t) \begin{cases} = \infty & , \text{ if } \quad p(t) > w(t)\big(1 + a(t)\big) + \tau_e(t)\big(1 - G(a(t))\big) \\ \in [0, \infty) & , \text{ if } \quad p(t) = w(t)\big(1 + a(t)\big) + \tau_e(t)\big(1 - G(a(t))\big) \\ = 0 & , \text{ if } \quad p(t) < w(t)\big(1 + a(t)\big) + \tau_e(t)\big(1 - G(a(t))\big) \end{cases} \ , \tag{34}$$

where the optimal abatement effort a is given by the solution of the implicit equation $\tau_e(t)G'(a(t)) = w(t)$ if $l_1(t) > 0$, and $a(t) = 0$ if $l_1(t) = 0$.

With an investment subsidy $\tau_i(t)$ paid per unit of investment i, the household's budget constraint equals:[7]

$$p(t)x(t) = w(t)\big(1 - i(t)\big) - \tau_i(t)i(t) + r(t)k(t) + \pi_1(t) + \pi_2(t) \ . \tag{35}$$

[7] For the sake of consistency, a positive τ_e (τ_i) denotes a tax and a negative τ_e (τ_i) denotes a subsidy.

Thus, the necessary and sufficient condition (21b) is replaced by:

$$q_b(t)\big(w(t)+\tau_i(t)\big) = q_k(t+\sigma) + q_i(t)\ . \tag{36}$$

Neither the emission tax τ_e nor the innovation subsidy τ_i directly affect firm 2, and thus the decision criteria of firm 2 remain unchanged.

5.2 Necessary and sufficient condition for the regulated market equilibrium

Given the adjusted equations (32) and (36), which replace equations (24) and (21b) of section 4, we analyze how the interior market equilibrium changes if an emission tax τ_e and an investment subsidy τ_i are enacted.

From conditions (33), (34) and (26) we derive the following conditions for an interior market equilibrium where both firms operate (i.e. $l_1(t) > 0$, $i(t) > 0$):

$$1 = \frac{\tau_e(t)}{p(t)}\big[G'(a(t))(1+a(t)) + 1 - G(a(t))\big]\ , \tag{37}$$

$$\frac{w(t)}{p(t)} = \frac{1 - \frac{\tau_e(t)}{p(t)}\big(1-G(a(t))\big)}{1+a(t)}\ , \tag{38}$$

$$\frac{r(t)}{p(t)} = \frac{1 + a(t) - \lambda + \lambda\frac{\tau_e(t)}{p(t)}\big(1-G(a(t))\big)}{\kappa(1+a(t))}\ . \tag{39}$$

Solving equation (21a) for q_b and taking into account conditions (39) we achieve for the shadow price of capital q_k:

$$q_k(t) = \frac{\exp[\gamma t]}{\kappa}\int_t^\infty \frac{1 + a(s) - \lambda + \lambda\frac{\tau_e(s)}{p(s)}\big(1-G(a(s))\big)}{1+a(s)} U'(x(s)) \exp[-(\gamma+\rho_p)s]\, ds\ . \tag{40}$$

Inserting q_b and equation (38) into equation (36) yields

$$\frac{1 - \frac{\tau_e(t)}{p(t)}\big(1-G(a(t))\big)}{1+a(t)} U'(x(t)) \exp[-\rho_p t] = q_k(t+\sigma) - \frac{\tau_i(t)}{p(t)} U'(x(t)) \exp[-\rho_p t]\ , \tag{41}$$

which together with equation (37) determines the interior market equilibrium for a given emission tax τ_e and investment subsidy τ_i. Note that equations (37) and (41) determine the market equilibrium only in terms of relative prices. Thus, one price can freely be chosen as a numeraire.

Choosing the price of energy p as numeraire we calculate the optimal emission tax and the optimal investment subsidy. Comparing equation (37) with the corresponding condition (11) in the social optimum we achieve for the optimal emission tax τ_e^{opt}:

$$\frac{\tau_e(t)^{opt}}{p(t)} = \frac{D'(e(t))}{U'(x(t))}\ . \tag{42}$$

For conditions (41) and (14) to coincide the investment subsidy τ_i^{opt} has to be set to:

$$\begin{aligned}\frac{\tau_i(t)^{opt}}{p(t)} &= -\frac{\exp[-\gamma(t+\sigma)]}{\kappa U'(x(t))}\int_{t+\sigma}^{\infty}\frac{U'(x(s))(1+a(s)-\lambda)+D'(e(s))\lambda\big(1-G(a(s))\big)}{1+a(s)} \\ &\quad \times\exp[-\gamma s]\big(\exp[-\rho(s-t)]-\exp[-\rho_p(s-t)]\big)\,ds\;. \qquad (43)\end{aligned}$$

Hence, if the two instruments are set in such a way that the market equilibrium is identical to the social optimum, τ_e^{opt} is always positive (i.e. emissions are taxed) and τ_i^{opt} is always negative (i.e. investment is subsidized).

In the following, we consider how the conditions for investment and replacement, i.e. the two corner solutions, change compared to the unregulated market economy when an emission tax τ_e is raised from firm 1 and an investment subsidy τ_i is paid to the household. We show that setting τ_e and τ_i as defined in equations (42) and (43) also implements the social optimum in the corner solutions.

5.3 Conditions for investment and replacement

Again, we first assume that the economy stays in the no investment corner solution. We derive a condition for positive investment to be a market equilibrium in the regulated market regime with emission tax τ_e and investment subsidy τ_i. The following proposition states this condition.

Proposition 5 (Investment condition in the regulated market regime)
Given the optimization problem (19) of the household with the adjusted budget constraint (35), the profit functions (32) and (25) of firm 1 and firm 2, and the emission tax $\frac{\tau_e(t)}{p(t)}$ and the investment subsidy $\frac{\tau_i(t)}{p(t)}$ in units of the numeraire p, the new technology is innovated in the market equilibrium, i.e. $i(t)>0$, if and only if the following condition holds:

$$1+a^0+\frac{1-G(a^0)}{G'(a^0)} > \lambda+\left[1+\frac{\tau_i^0}{\tau_e^0 G'(a^0)}\right]\kappa(\gamma+\rho_p)\exp[\rho_p\sigma]\;, \qquad (44)$$

where $\tau_e^0=\frac{\tau_e(t)}{p(t)}$, $\tau_i^0=\frac{\tau_i(t)}{p(t)}$ evaluated at the no investment stationary state and a^0 is determined by the unique solution of the implicit equation:

$$1=\tau_e^0\big(G'(a^0)(1+a^0)+1-G(a^0)\big)\;. \qquad (45)$$

Condition (44) for the market equilibrium is identical to the corresponding condition for the social optimum (14), if τ_e^0 and τ_i^0 are set as follows:

$$\tau_e^0 = \frac{D'(e^0)}{U'(x^0)} > 0\;, \qquad (46)$$

$$\tau_i^0 = \frac{D'(e^0)\big[(1+a^0-\lambda)G'(a^0)+1-G(a^0)\big]}{\kappa U'(x^0)}\left(\frac{\exp[-\rho_p\sigma]}{\gamma+\rho_p}-\frac{\exp[-\rho\sigma]}{\gamma+\rho}\right) < 0\;, \qquad (47)$$

where $x^0=1-a^0$ and $e^0=(1-a^0)(1-G(a^0))$.

Proof: See Appendix A.8.

Condition (44) displays the unit costs of energy production of the established and of the new technology in the no investment market equilibrium when an emission tax τ_e is imposed and an innovation subsidy τ_i is paid. Imposing the emission tax τ_e enforces the incorporation of the social costs of emissions into the unit costs of production of the established technology. By setting τ_e^0 equal to the ratio between marginal damage from environmental degradation and marginal benefit from consumption the unit costs of production of the established technology are raised to their socially optimal level and thus the emission externality is internalized. However, it is obvious from condition (44) that an emission tax does not suffice for the market equilibrium to resemble the socially optimal outcome. In addition, an investment subsidy has to be paid, lowering the unit costs of energy production for the new technology to their level at the social optimum. Note that conditions (46) and (47) are identical to the corresponding conditions (42) and (43) for an interior market equilibrium evaluated at the no investment corner solution.

We will now derive the conditions for which full replacement of the established by the new technology is a market equilibrium in the long run, given that the state imposes an emission tax τ_e and pays an investment subsidy τ_i.

Proposition 6 (Full replacement condition in the regulated market regime) *Given the optimization problem (19) of the household with the adjusted budget constraint (35), the profit functions (32) and (25) of firm 1 and firm 2, the emission tax $\frac{\tau_e(t)}{p(t)}$ and the investment subsidy $\frac{\tau_i(t)}{p(t)}$, full replacement of the established technology by the new one in the long-run stationary state is consistent with the necessary and sufficient conditions for a regulated market equilibrium, if and only if the following condition holds:*

$$1 + \frac{\tau_e^\infty}{1-\tau_e^\infty} \geq \lambda + \left[1 + \frac{\tau_i^\infty}{1-\tau_e^\infty}\right] \kappa(\gamma+\rho_p)\exp[\rho_p\sigma] \ , \tag{48}$$

where $\tau_e^\infty = \frac{\tau_e(t)}{p(t)}$, $\tau_i^\infty = \frac{\tau_i(t)}{p(t)}$ evaluated at the long-run stationary state.

Condition (48) for the market equilibrium is identical to the corresponding condition for the social optimum (16), if τ_e^∞ and τ_i^∞ are set as follows:

$$\tau_e^\infty = \frac{D'(0)}{U'(x^\infty)} \geq 0 \ , \tag{49}$$

$$\tau_i^\infty = \frac{U'(x^\infty)(1-\lambda) + D'(0)\lambda}{\kappa U'(x^\infty)} \left(\frac{\exp[-\rho_p\sigma]}{\gamma+\rho_p} - \frac{\exp[-\rho\sigma]}{\gamma+\rho}\right) < 0 \ , \tag{50}$$

where $x^\infty = \frac{1}{\lambda+\kappa\gamma}$.

Proof: See Appendix A.9.

Note that, although in the case of full replacement the external effect from the emissions vanishes, the emission tax has to be raised if $D'(0) > 0$ for the market equilibrium to resemble the social optimum. If $D'(0) = 0$, then the optimal tax in the full replacement stationary state is given by $\tau_e^\infty = 0$. However, the optimal investment subsidy τ_i^∞ has to be negative in any case.

As in the social optimum, conditions (44) and (48) have to hold simultaneously for full replacement to occur in the regulated market regime in the long run. Moreover, if the emission tax τ_e and the investment subsidy τ_i are such that condition (44) is always fulfilled but condition (48) is always violated, the economy exhibits a market equilibrium where both technologies are used, i.e. there is a partial replacement of the established by the new technique.

6 Discussion

Before discussing model assumptions and policy implications, we briefly summarize our findings. Recall that there are two energy technologies available in the economy. The first gives rise to emissions which can be partly abated by an end-of-pipe technology. The resulting net emissions impose a negative externality on society. The second is clean but needs some time σ before investment becomes productive. Moreover, the intertemporal valuation is deterred by the split between the private and social rates of time preference. Whether the second technology (partly) replaces the first one hinges on the exogenously given parameters and on whether and to what extent the emission externality and the split of time preferences are corrected by an emission tax τ_e and an investment subsidy τ_i. Figure 1 illustrates the findings.

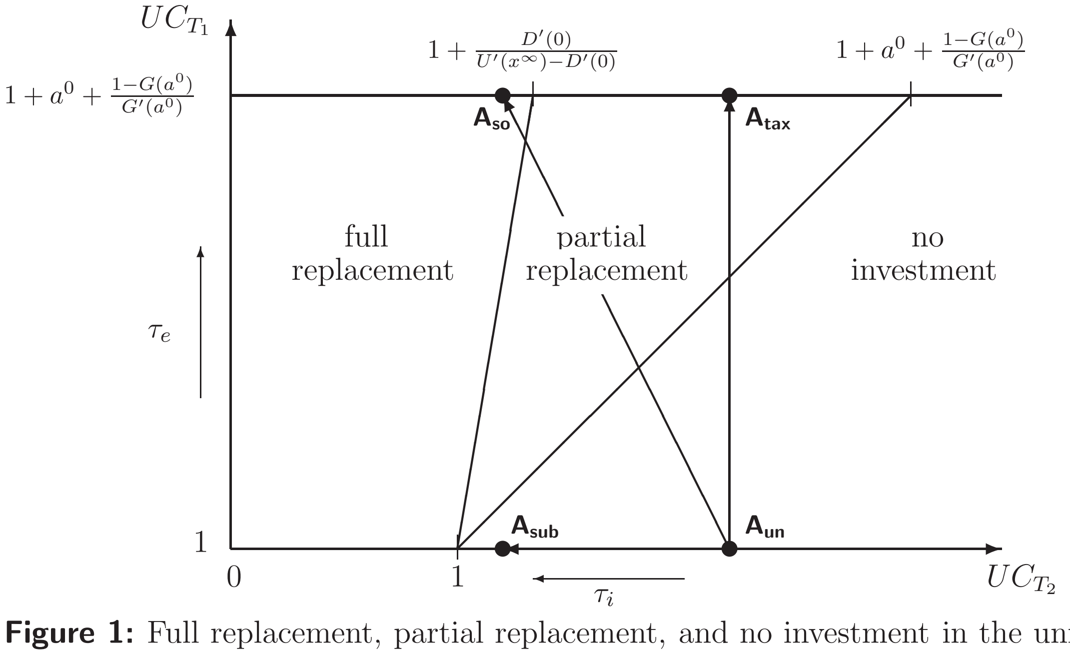

Figure 1: Full replacement, partial replacement, and no investment in the unregulated market equilibrium and the social optimum.

In the unregulated market regime UC_{T_1} always equals 1. Thus, the combination of the unit costs of production of the two technologies associated with the investment and replacement conditions is always represented by a point on the UC_{T_2} axis in Figure 1. For example, point A denotes a situation where no investment in the new technology takes place in the unregulated market regime, though full replacement would be socially optimal (point A_{so}). Imposing an emission tax τ_e increases the unit costs of the established technology (upwards shift in Figure 1). In the social optimum the unit costs of the established technology equal $1 + a^0 + \frac{1-G(a^0)}{G'(a^0)}$. The introduction of an investment subsidy decreases the unit costs of the new technology shifting the UC_{T_2} to the left. In general, the social optimum in a market regime can only be implemented by combining environmental and technology policies (moving from A_{un} to A_{so}). In the example in Figure 1, the sole imposition of the emission tax would lead to a partial replacement of the established technology (shift from A_{un} to A_{tax}), and the sole imposition of the investment subsidy leaves the economy in the no-investment stationary state (shift from A_{un} to A_{sub}).

In sum, environmental policy alone tends to favor gradual over structural change as private investors overestimate the unit costs of the new technology compared to the social optimum. On the other hand, technology policy alone induces no gradual change because the negative externality imposed by the emissions is not taken into account. As no abatement effort is undertaken and, hence, the unit costs of the established technology are underestimated, structural change is in tendency disadvantaged compared to the social optimum.

6.1 Model assumptions

The crucial assumption for our results to hold is that the social and individual rates of time preference differ. In section 2 we discussed different reasons for the split particularly relevant in the present context. However, to keep our model tractable we have abstained from an endogenous explanation and focused on its effect. The split of time preference rates is the more important the more the consequences of actions undertaken today spread into the future. The shift from a carbon-intensive to a carbon-neutral energy industry happens on a timescale of several decades. Thus, in the context of mitigating climate change even a small split between the private and social rate of time preference can have a significant impact.

The other distinctive feature of our model, the time-lagged accumulation of the specific capital good of the new technology, is not crucial for our qualitative results, but amplifies the overestimation of the unit costs of production of the new technology caused by the split in time preference rates. The energy industry is a prime example for exhibiting substantial time-lags between the costs of investment and new capital to become productive. As a consequence, we consider the split in time preferences to be particularly important in the context of the technological transition of energy systems where both long time horizons and substantial time lags come together. In our opinion, this justifies the additional mathematical obstacles incurred by the time-lagged equation of motion.

In our model we consider a flow pollutant, whereas the accumulation of greenhouse gases in the atmosphere causing the rise of global mean temperature is a stock-pollutant problem. This simplification does not qualitatively affect our results. Rather, for a stock pollutant, the split of time preference rates would imply an underestimation of the future damages from emissions today by the individual households compared to the social planner. As a consequence, the unit costs of production of the established technology would be further underestimated in the unregulated market economy.

By modeling the energy technologies as linear and linear-limitational, we assume very specific functional forms. The rationale is to account for the rigidities in energy production due to technical and thermodynamic constraints. From a more technical point of view, it is the linearity of the production functions which gives rise to the corner solutions, which we exploit to derive conditions of investment and partial and full replacement. As our focus is on the substitution effects *between* (the established and the new) energy production technologies, the analysis abstracts from substitution possibilities among different production factors *within* the individual energy technologies. Moreover, taking a medium-term perspective, we abstract from some typical long-run problems. First, we neglect endogenous technological change in the sense that new technologies emerge or technologies become more efficient over time. Second, we do not consider fuel inputs explicitly and thus implicitly assume the finiteness of conventional energy sources to be non-binding over the relevant time horizon. Finally, we abstract from growth. Obviously, all these characteristics are important for successful climate-change mitigation strategies but are not in the primary focus of our paper.

Finally, for the sake of a tractable model we abstract from a series of peculiarities of the economics of electric power systems. First, the energy industry is subject to cyclical demand fluctuations on different time-scales (for example day/night-time or summer/winter). As different energy technologies exhibit different turn-on/turn-off costs and rigidities, a mix of energy technologies is in general preferable over 'energy monocultures'. Second, in contrast to our assumption of a perfectly competitive market, the energy industry rather exhibits an oligopolistic market structure. As is well known from the industrial organization literature, unregulated oligopolistic market regimes lead in general to additional market failures, from which we abstract to concentrate on the distortions imposed by emissions and diverging time preference rates.

6.2 Policy implications

Although the analysis has been carried out in a highly stylized theoretical framework, direct policy implications can be drawn which are relevant for the regulation of the energy industry and the optimal transition towards a cleaner energy system.

First, the analysis implies that for the transition towards a low-emission energy industry the imposition of an environmental tax alone is in general not sufficient to implement the socially optimal path.[8] Rather, technology policy should complement environmental policy. As a general result, this is not new. For, there is a series of well established causes for technology policy associated with the process of technological transformation (e.g. Jaffe et al. 2005). We derive this result without considering these cases. In our model, it is the split of social and private time preference rates combined with the time-consuming

[8] The equivalent result holds for the sole introduction of an emission permit trade scheme.

nature of bringing a new technology into use which leads to the additional distortion.

Second, our analysis gives new theoretical support for policies that subsidize clean energy technologies. According to our analysis the level of the subsidy should depend, apart from the difference in time preference rates, on the labor intensity (λ), capital intensity (κ), rate of capital depreciation (γ), and time lag in construction (σ) of the new technology. Thus, we are rather skeptical about the efficiency of policies such as the German "Erneuerbare-Energien-Gesetz" (Renewable Energy Sources Act) that subsidizes only renewable energy technologies by feed-in tarifs oriented at the level of their unit costs of production.[9]

Finally, in the environmental economics literature there has been a broad and often critical discussion of Porter and van der Linde's (1995) claim that a "well-designed" environmental regulation may exhibit a double dividend in the sense of achieving both less pollution and a higher competitiveness. The present analysis substantiates their claim with respect to what constitutes a "well-designed" environmental regulation. As obvious from the formulae of the unit costs of production of the established and the new technology, gradual technological change always induces additional costs to the existing technology, whereas structural technological change may exhibit higher, equal or lower unit costs of production compared to the pure labor costs of the established technology. It is the latter case in which the new technology offers a double dividend in the sense of the Porter hypothesis (no emissions and lower unit costs).

7 Conclusion

In this paper, we study the interplay between gradual and structural change in the transition from an established polluting to a new clean energy technology. We develop a dynamic general equilibrium model, where (i) the social stays below the private rate of time preference, (ii) the creation of new productive capital is time-lagged, (iii) emissions are negatively valued, and (iv) an (end-of-pipe) abatement technology is available. We derive the ratio of the unit costs of energy of the two technologies as the decisive criterion whether investment in the new and partial or full replacement of the established technology occur.

We provide a new reason why environmental policy has to be supplemented by technology policy such as a non-distortionary investment subsidy, in order to achieve the social optimum in a market regime. If only an emission tax is enacted the investment decision is biased in favor of gradual technological change compared to the social optimum, as the costs of structural change are overestimated by private investors. Our results constructively contribute to the Kyoto conflict between the United States and the European Union. Instead of asking which of the two policies to apply, our findings indicate that the correct question is how to optimally combine both policies.

[9] At least from a medium-term perspective, which does not take into account long-run dynamic effects like learning curves or induced technological change, the very high subsidies for photovoltaics (45.7–62.4 €-cent per kWh, compared to 5.5–9.1 for wind energy and 7.16–15 for geothermal energy) raise doubts about their efficient use in Germany.

Of course, the analysis provides only a theoretical indication. It is up to further empirical research to investigate how social and individual preferences actually differ in the case of essential and desired goods, such as energy, the production of which is necessarily linked to the by-production of a harmful joint output. This is particularly important to derive concrete levels of investment subsidies for technology policies. Moreover, we did not take into account the oligopolistic market structures which are common in energy markets and the integration of which into our model constitutes a fruitful agenda for further theoretical research.

Appendix

A.1 Concavity of the Hamiltonian along the optimal path

In the following, we show that the maximized Hamiltonian $\mathcal{H}^0$ is jointly concave in the variables x, e, and k along the optimal path. $\mathcal{H}^0$ is the Hamiltonian $\mathcal{H}$ as defined in equation (9) in which the optimal paths for a and i are substituted. Although we cannot derive the optimal paths for a and i, we can eliminate them by employing the necessary conditions for an optimal solution.

The Hamiltonian (9) can be written as:

$$\begin{aligned}\mathcal{H} \;=\;& [U(x(t)) - D(e(t))]\exp[-\rho t] + q_x(t)\left[\frac{1}{\kappa}k(t) - x(t)\right] - q_e(t)e(t)\\ &+ q_k(t+\sigma)i(t) - q_k(t)\gamma k(t) + q_i(t)i(t) + q_{l_1}\frac{1-\frac{\lambda}{\kappa}k(t) - i(t)}{1+a(t)}\\ &+ \frac{1-\frac{\lambda}{\kappa}k(t)-i(t)}{1+a(t)}\left[q_x(t) + q_e(t)\big(1-G(a(t))\big)\right] \;.\end{aligned} \tag{A.1}$$

From the necessary condition (10d), we know that

$$\frac{q_x(t) + q_e(t)\big(1-G(a(t))\big)}{1+a(t)} \;=\; q_k(t+\sigma) + q_i(t) - \frac{q_{l_1}(t)}{1+a(t)} \;. \tag{A.2}$$

Inserting equation (A.2) into equation (A.1) yields the maximized Hamiltonian $\mathcal{H}^0$, in which the control variables a and i are eliminated:

$$\begin{aligned}\mathcal{H}^0 \;=\;& [U(x(t)) - D(e(t))]\exp[-\rho t] + q_x(t)\left[\frac{1}{\kappa}k(t) - x(t)\right] - q_e(t)e(t)\\ &+ q_k(t+\sigma)\left[1-\frac{\lambda}{\kappa}k(t)\right] - q_k(t)\gamma k(t) \;.\end{aligned} \tag{A.3}$$

Obviously, $\mathcal{H}^0$ is strictly concave, as it is the sum of concave and strictly concave functions.

□

A.2 Optimal transition dynamics and stationary states

The optimal system dynamics of the optimization problem (8) splits into three cases. The first case corresponds to the corner solution $i(t) = 0 \;\forall\, t$. In this case, there is no system dynamics at all. The system will remain in a stationary state where the labor endowment is fully used up by energy production via the established technology and by abatement.

In the second case, the optimal system dynamics is an interior solution, i.e. $i(t) > 0$ and $l_1(t) > 0 \;\forall\, t$ holds along the optimal path. Then, the system dynamics is governed by the following system of differential equations:

$$\begin{aligned}\frac{di(t)}{dt} &= \Phi_1(t)\left[(\gamma+\rho)D'(t)G'(t) + \frac{\exp[-\rho\sigma]}{\kappa}\big(\lambda D'(t{+}\sigma)G'(t{+}\sigma) + U'(t{+}\sigma)\big)\right] \\ &\quad + \Phi_2(t)\left[i(t{-}\sigma) - \gamma k(t)\right] \;, &\text{(A.4a)}\\ \frac{da(t)}{dt} &= \Phi_3(t)\left[(\gamma+\rho)D'(t)G'(t) + \frac{\exp[-\rho\sigma]}{\kappa}\big(\lambda D'(t{+}\sigma)G'(t{+}\sigma) + U'(t{+}\sigma)\big)\right] \\ &\quad + \Phi_4(t)\left[i(t{-}\sigma) - \gamma k(t)\right] \;, &\text{(A.4b)}\\ \frac{dk(t)}{dt} &= i(t{-}\sigma) - \gamma k(t) \;, &\text{(A.4c)}\end{aligned}$$

where $\Phi_n(t)$ $(n = 1, \ldots, 4)$ are functions of $i(t)$, $a(t)$ and $k(t)$, as shown in Appendix A.3 below. As $\frac{di(t)}{dt}$, $\frac{da(t)}{dt}$ and $\frac{dk(t)}{dt}$ also depend on *advanced* (i.e. at a later time) and on *retarded* (i.e. at an earlier time) variables, equations (A.4) form a system of *functional differential equations*.[10] In general, this system is not analytically soluble (not even in the linear approximation around the stationary state). However, we show in Appendix A.3 that the unique stationary state, given by the following implicit equations:

$$\begin{aligned}U'(x^\star) &= D'(e^\star)\left[G'(a^\star)\,(1+a^\star) + 1 - G(a^\star)\right] \;, &\text{(A.5a)}\\ \gamma+\rho &= \exp[-\rho\sigma]\frac{\lambda D'(e^\star)G'(a\star) + U'(x^\star)}{\kappa D'(e^\star)G'(a^\star)} \;, &\text{(A.5b)}\\ i^\star &= \gamma k^\star \;, &\text{(A.5c)}\end{aligned}$$

is a saddle point. Hence, for all sets of initial conditions there is a unique optimal path which converges towards the stationary state. In general, these optimal paths are oscillatory and exponentially damped.[11]

In the third case, which corresponds to the corner solution $l_1(t) = 0$, the established technology will eventually be fully replaced by the new technology, and all labor is used to employ and maintain the capital stock k. Thus, if the restriction $l_1(t) \geq 0$ is binding, there exists a direct link between capital stock k and investment i:

$$k(t) = \frac{\kappa}{\lambda}(1 - i(t)) \;. \tag{A.6}$$

Differentiating with respect to time t and inserting into the equation of motion for the capital stock (8d), yields the following linear first-order differential-difference equation of the retarded type, which governs the system dynamics:

$$\frac{di(t)}{dt} + \gamma i(t) + \frac{\lambda}{\kappa} i(t{-}\sigma) = \gamma \;. \tag{A.7}$$

[10] For an introduction to functional differential equations see Asea and Zak (1999: section 2) and Gandolfo (1996: chapter 27). A detailed exposition of linear functional differential equations is given in Bellman and Cooke (1963) and Hale (1977).

[11] The system of functional differential equations (A.4) may also exhibit so-called *limit-cycles*, i.e. the optimal paths oscillate around the stationary state without converging towards or diverging from it (e.g. Asea and Zak 1999).

The solution to this equation is analyzed in detail in Winkler et al. (2005). In general, the optimal paths converge oscillatorily and exponentially damped towards the stationary state, which is given by

$$i^\star = \frac{\kappa\gamma}{\lambda + \kappa\gamma} \ , \qquad k^\star = \frac{\kappa}{\lambda + \kappa\gamma} \ . \tag{A.8}$$

□

A.3 Saddle point stability of the interior solution

In order to show the saddle point property of the stationary state in the case of an interior solution, i.e. if $i(t) > 0$ and $l_1(t) > 0 \ \forall \, t$ along the optimal path, we investigate the following general maximization problem:

$$\max_{a(t),i(t)} \int_0^\infty F(i(t), a(t), k(t)) \exp[-\rho t] \, dt \tag{A.9a}$$

subject to

$$\dot{k} \ = \ i(t{-}\sigma) - \gamma k(t) \ , \tag{A.9b}$$
$$i(t) \ = \ \xi(t) \ = \ 0, \qquad t \in [-\sigma, 0) \ , \tag{A.9c}$$

which is equivalent to the optimization problem (8) in the case of an interior solution with

$$F = U\left(\frac{1 - \frac{\lambda}{\kappa}k(t) - i(t)}{1 + a(t)} + \frac{k(t)}{\kappa}\right) - D\left((1 - G(a(t)))\frac{1 - \frac{\lambda}{\kappa}k(t) - i(t)}{1 + a(t)}\right) \ . \tag{A.10}$$

The corresponding present-value Hamiltonian reads

$$\mathcal{H} = F(t) \exp[-\rho t] + q(t{+}\sigma) i(t) - q(t) \gamma k(t) \ , \tag{A.11}$$

where q denotes the shadow price for the state variable k.

If the maximized Hamiltonian (A.11) is strictly concave, which is assumed in the following, the following conditions are necessary and sufficient for an optimal solution:[12]

$$q(t{+}\sigma) \ = \ -F_i(t) \exp[-\rho t] \ , \tag{A.12a}$$
$$F_a(t) \ = \ 0 \ , \tag{A.12b}$$
$$\dot{q}(t) \ = \ -F_k(t) \exp[-\rho t] + \gamma q(t) \ , \tag{A.12c}$$
$$\lim_{t\to\infty} q(t) k(t) \ = \ 0 \ . \tag{A.12d}$$

Differentiating equations (A.12a) and (A.12b) with respect to time t, inserting (A.12a), (A.12c) and (A.9b) into the resulting equations, and solving for $\frac{di(t)}{dt}$, $\frac{da(t)}{dt}$ and $\frac{dk(t)}{dt}$ yields the

[12] In the following, for presentational convenience, partial derivatives are denoted by subscripts and only the time argument is stated explicitly.

following set of functional differential equations:

$$\begin{aligned}
\frac{di(t)}{dt} &= \frac{F_{aa}(t)}{\Delta F(t)}\left[(\gamma+\rho)F_i(t)+\exp[-\rho\sigma]F_k(t{+}\sigma)\right] \\
&\quad + \frac{F_{ia}(t)F_{ak}(t)-F_{aa}(t)F_{ik}(t)}{\Delta F(t)}\left[i(t{-}\sigma)-\gamma k(t)\right] \ , && \text{(A.13a)} \\
\frac{da(t)}{dt} &= \frac{F_{ia}(t)}{\Delta F(t)}\left[(\gamma+\rho)F_i(t)+\exp[-\rho\sigma]F_k(t{+}\sigma)\right] \\
&\quad + \frac{F_{ia}(t)F_{ik}(t)-F_{ii}(t)F_{ak}(t)}{\Delta F(t)}\left[i(t{-}\sigma)-\gamma k(t)\right] \ , && \text{(A.13b)} \\
\frac{dk(t)}{dt} &= i(t{-}\sigma)-\gamma k(t) \ , && \text{(A.13c)}
\end{aligned}$$

where $\Delta F(t) \equiv F_{ii}(t)F_{aa}(t) - F_{ia}(t)^2$.

Introducing the following abbreviations:

$$\Phi_1(t) = \frac{F_{aa}(t)}{\Delta F(t)} \ , \qquad \Phi_2(t) = \frac{F_{ia}(t)F_{ak}(t)-F_{aa}(t)F_{ik}(t)}{\Delta F(t)} \ ,$$

$$\Phi_3(t) = -\frac{F_{ia}(t)}{\Delta F(t)} \ , \quad \Phi_4(t) = \frac{F_{ia}(t)F_{ik}(t)-F_{ii}(t)F_{ak}(t)}{\Delta F(t)} \ ,$$

and inserting $F_i(t)$ and $F_k(t{+}\sigma)$ yields the system of differential equations (A.4).

In the stationary state, $\frac{di(t)}{dt} = \frac{da(t)}{dt} = \frac{dk(t)}{dt} = 0$ holds. Thus, the unique stationary state $(i^\star, a^\star, k^\star)$ is determined by the three implicit equations:

$$\begin{aligned}
\gamma+\rho &= -\exp[-\rho\sigma]\frac{F_i(i^\star,a^\star,k^\star)}{F_k(i^\star,a^\star,k^\star)} \ , && \text{(A.14)} \\
0 &= F_a(i^\star,a^\star,k^\star) \ , && \text{(A.15)} \\
i^\star &= \gamma k^\star \ . && \text{(A.16)}
\end{aligned}$$

Inserting F_i, F_a and F_k yields the equations (A.5).

In order to investigate the stability properties of optimization problem (A.9) in a neighborhood around the stationary state $(i^\star, a^\star, k^\star)$, we linearize the system of functional differential equations (A.13) around the stationary state. Therefore, we first introduce the new variables

$$\hat{i}(t) = i(t) - i^\star \ , \quad \hat{a}(t) = a(t) - a^\star \ , \quad \hat{k}(t) = k(t) - k^\star \ . \qquad \text{(A.17)}$$

Applying the first-order Taylor approximation of the system (A.13) around the stationary state $(i^\star, a^\star, k^\star)$ yields:

$$\begin{aligned}
\frac{d\hat{i}(t)}{dt} &\approx \Phi_1\exp[-\rho\sigma]\left[F_{ik}i(t{+}\sigma)-\frac{F_{ii}F_k}{F_i}i(t)+F_{ak}a(t{+}\sigma)-\frac{F_{ia}F_k}{F_i}a(t)+F_{kk}k(t{+}\sigma)\right. \\
&\quad \left. -\frac{F_{ik}F_k}{F_i}k(t)\right] + \Phi_2\left[u(t{-}\sigma)-\gamma k(t)\right] \ , && \text{(A.18a)} \\
\frac{d\hat{a}(t)}{dt} &\approx \Phi_3\exp[-\rho\sigma]\left[F_{ik}i(t{+}\sigma)-\frac{F_{ii}F_k}{F_i}i(t)+F_{ak}a(t{+}\sigma)-\frac{F_{ia}F_k}{F_i}a(t)+F_{kk}k(t{+}\sigma)\right. \\
&\quad \left. -\frac{F_{ik}F_k}{F_i}k(t)\right] + \Phi_4\left[u(t{-}\sigma)-\gamma k(t)\right] \ , && \text{(A.18b)} \\
\frac{d\hat{k}(t)}{dt} &\approx u(t{-}\sigma)-\gamma k(t) \ , && \text{(A.18c)}
\end{aligned}$$

where all functions are evaluated at the stationary state $(i^\star, a^\star, k^\star)$. Similar to the case of ordinary linear first-order differential equations, the elementary solutions for $\hat{\imath}$, $\hat{a}$ and $\hat{k}$ are exponential functions, and the general solution is given by the superposition of the elementary solutions

$$\hat{\imath}(t) \approx \sum_n i_n \exp[z_n t] \ , \quad \hat{a}(t) \approx \sum_n a_n \exp[z_n t] \ , \quad \hat{k}(t) \approx \sum_n k_n \exp[z_n t] \ , \tag{A.19}$$

where the i_n, a_n and k_n are constants, which can (at least in principle) be unambiguously determined by the set of initial conditions and the transversality condition. The *eigenvalues* z_n are the roots of the *characteristic polynomial* $Q(z)$. The characteristic polynomial $Q(z)$ for the system of differential-difference equations (A.18) is given by the determinant of the Jacobian of (A.18) minus the identity matrix times z:

$$Q(z) = \begin{vmatrix} A_{11} - z & A_{12} & A_{13} \\ A_{21} & A_{22} - z & A_{23} \\ A_{31} & A_{32} & A_{33} - z \end{vmatrix} \ , \tag{A.20a}$$

where

$$\begin{aligned}
A_{11} &= \Phi_1 \left\{ F_{ik}\big(\exp[\sigma(z-\rho)] - \exp[-\sigma z]\big) + F_{ii}(\gamma+\rho) \right\} + \frac{F_{ia}F_{ak}}{\Delta F} \exp[-\sigma z] \ , && \text{(A.20b)}\\
A_{12} &= \Phi_1 \big\{ F_{ak} \exp[\sigma(z-\rho)] + F_{ia}(\gamma+\rho) \big\} \ , && \text{(A.20c)}\\
A_{13} &= \Phi_1 \big\{ F_{kk} \exp[\sigma(z-\rho)] + F_{ik}(2\gamma+\rho) \big\} - \frac{F_{ia}F_{ak}}{\Delta F}\gamma \ , && \text{(A.20d)}\\
A_{21} &= \Phi_2 \left\{ F_{ik}\big(\exp[\sigma(z-\rho)] - \exp[-\sigma z]\big) + F_{ii}(\gamma+\rho) \right\} - \frac{F_{ii}F_{ak}}{\Delta F} \exp[-\sigma z] \ , && \text{(A.20e)}\\
A_{22} &= \Phi_2 \big\{ F_{ak} \exp[\sigma(z-\rho)] + F_{ia}(\gamma+\rho) \big\} \ , && \text{(A.20f)}\\
A_{23} &= \Phi_2 \big\{ F_{kk} \exp[\sigma(z-\rho)] + F_{ik}(2\gamma+\rho) \big\} + \frac{F_{ii}F_{ak}}{\Delta F}\gamma \ , && \text{(A.20g)}\\
A_{31} &= \exp[-\sigma z] \ , && \text{(A.20h)}\\
A_{32} &= 0 \ , && \text{(A.20i)}\\
A_{33} &= -\gamma \ . && \text{(A.20j)}
\end{aligned}$$

Thus, one obtains for the characteristic polynomial $Q(z)$:

$$\begin{aligned}
Q(z) &= -(z-\gamma-\rho)(z+\gamma) + \Phi_2 \big\{ (z-\gamma-\rho)\exp[-\sigma z] - (z+\gamma)\exp[\sigma(z-\rho)] \big\} \\
&\quad + \frac{F_{aa}F_{kk} - F_{ak}^2}{\Delta F} \exp[-\sigma\rho] \ . && \text{(A.21)}
\end{aligned}$$

$Q(z)$ is a *quasi-polynomial*, which exhibits an infinite number of complex roots.

In order to determine whether the stationary state is a saddle point, we need to know the signs of the real parts of the characteristic roots. Therefore, we show that the characteristic polynomial $Q(z)$ has an infinite number of roots with negative real part and an infinite number of roots with positive real part and, thus, the stationary state is a saddle point.

First, note that the characteristic roots of $Q(z)$ are symmetric around $\rho/2$, i.e., if z^0 is a characteristic root, then $\rho - z^0$ is also a characteristic root (one can easily verify that

$Q(z^0) = Q(\rho - z^0)$). Second, in order to apply Theorem 13.1 of Bellman and Cooke (1963: 441), we introduce the new variable $y = \sigma z$ and multiply Q with $\sigma^2 \exp[y]$

$$\begin{aligned} Q(y) &= -(y - \sigma\gamma - \sigma\rho)(y + \sigma\gamma)\exp[y] - \sigma\Phi_2\big\{(y - \sigma\gamma - \sigma\rho) - (y + \sigma\gamma)\exp[2y - \sigma\rho]\big\} \\ &\quad + \sigma^2 \frac{F_{aa}F_{kk} - F_{ak}^2}{\Delta F}\exp[y - \sigma\rho] \ . \end{aligned} \tag{A.22}$$

As $Q(y)$ has no *principal term*, i.e. a term, where the highest power of y and the highest exponential term appear jointly,[13] $Q(y)$ has "an unbounded number of zeros with arbitrarily large positive real part" (ibid). However, as the characteristic roots are symmetric around $\rho/2$, this implies that $Q(y)$ has also an unbounded number of roots with arbitrarily large negative real part.

□

A.4 Proof of Proposition 1

Assume that it is *optimal not to invest* at all times t. As a consequence, the economy will remain in the no investment corner solution where no capital is accumulated. Hence, $i(t) = 0$, $q_i(t) \geq 0 \ \forall t$ and inequality (8e) is binding. All energy is solely produced by the established production technique which implies that $x^0 = x_1^0 = 1 - a^0$, $x_2^0 = 0$, $l_1^0 > 0$ and inequality (8f) is not binding (i.e. $q_{l_1} = 0$). The optimal abatement effort a^0 is determined by equation (11) by inserting $x^0 = 1 - a^0$ and $e^0 = x^0(1 - G(a^0))$ which yields equation (15). Due to the assumed curvature properties of U, D and G, there exists a unique solution for a^0.

In the corner solution $i(t) = 0$, we derive the shadow price of capital $q_k^0(t)$ by inserting equation (11) in equation (12) and solving the integral:

$$q_k^0(t) = D'(e^0)\Big[(1 + a^0 - \lambda)G'(a^0) + 1 - G(a^0)\Big]\frac{\exp[-\rho t]}{\kappa(\gamma + \rho)} \ . \tag{A.23}$$

Equating conditions (10c), and (10d) and inserting equations (10b) and $q_k^0(t + \sigma)$ yields the following necessary and sufficient condition for the corner solution to be optimal:

$$D'(e^0)G'(a^0)\exp[-\rho t] - q_i(t) = D'(e^0)\Big[(1 + a^0 - \lambda)G'(a^0) + 1 - G(a^0)\Big]\frac{\exp[-\rho(t + \sigma)]}{\kappa(\gamma + \rho)} \ . \tag{A.24}$$

Taking into account that $q_i(t) \geq 0$, dividing by $D'(e^0)G'(a^0)$ and rearranging terms yields:

$$1 + a^0 + \frac{1 - G(a^0)}{G'(a^0)} \leq \lambda + \kappa(\gamma + \rho)\exp[\rho\sigma] \ . \tag{A.25}$$

Note that condition (A.25) is independent of t. This implies that it is optimal not to invest at all times t, if it is optimal not to invest at time $t = 0$. Thus, if condition (A.25) holds, the optimal solution of the optimization problem (8) is to remain in the no investment corner solution forever.

This, in turn, implies that it is *optimal to invest* in the new technology, if and only if condition (A.25) does not hold, which is exactly what condition (14) states.

□

[13] In this case, the principal term would be a term with $y^2 \exp[2y]$.

A.5 Proof of Proposition 2

Assume that it is optimal in the long-run stationary state to use the total labor endowment to employ and maintain the capital stock for the new technology, i.e. $x_2^\infty = \frac{1}{\lambda+\kappa\gamma}$. Then, all output is solely produced by the new technology, i.e. $x^\infty = x_2^\infty$, $x_1^\infty = l_1^\infty = 0$. In addition, no emissions are produced and have to be abated, and thus $e^\infty = 0$ and $a^\infty = 0$.

Inserting conditions (10a) and (10b) into equation (10e) yields:[14]

$$-\frac{dq_k^\infty(t)}{dt} = \frac{U'(x^\infty)(1-\lambda) + D'(0)\lambda - q_{l_1}^\infty \lambda}{\kappa} \exp[-\rho t] - q_k(t)\gamma \ . \tag{A.26}$$

Together with the transversality condition (10h), equation (A.26) can be solved to yield:

$$q_k^\infty(t) = \frac{\exp[-\rho t]}{\kappa(\gamma+\rho)} \left[U'(x^\infty)(1-\lambda) + D'(0)\lambda - q_{l_1}^\infty \lambda\right] \ . \tag{A.27}$$

By inserting conditions (10a), (10b) and $q_k^\infty(t+\sigma)$ into equation (10d), and taking into account that $q_{l_1}^\infty \geq 0$, we derive condition (16).

□

A.6 Proof of Proposition 3

Assume that it is *optimal not to invest* at all times t. As a consequence, the economy will remain in the no investment corner solution where no capital is accumulated. Hence, $i(t) = 0$, $q_i(t) \geq 0 \ \forall t$ and inequality (21d) is binding. All energy is solely produced by the established production technique (i.e. $x^0 = x_1^0 = 1$, $x_2^0 = 0$).

From the demand correspondences (24) and (26) we know that

$$\frac{w(t)}{p(t)} = 1 \ , \quad \frac{r(t)}{p(t)} \geq \frac{1}{\kappa}\left(1 - \lambda \frac{w(t)}{p(t)}\right) = \frac{1-\lambda}{\kappa} \ . \tag{A.28}$$

Solving equation (21a) for q_b and inserting it, together with conditions (A.28), in equation (22) yields the following inequality for the shadow price of capital:

$$q_k^0(t) \geq \frac{1-\lambda}{\kappa(\gamma+\rho_p)} U'(1) \exp[-\rho_p t] \ . \tag{A.29}$$

Inserting $q_b(t)$ and $q_k^0(t+\sigma)$ into equation (21b) and taking into account that $q_i(t) \geq 0$ yields the following necessary and sufficient condition for the corner solution to be a market equilibrium:

$$U'(1) \exp[-\rho_p t] \geq \frac{1-\lambda}{\kappa(\gamma+\rho_p)} U'(1) \exp[-\rho_p(t+\sigma)] \ . \tag{A.30}$$

Dividing by $U'(1)\exp[-\rho_p t]$ and rearranging terms yields that it is *optimal to invest* in the new technology, if and only if condition (30) holds.

□

[14] Note that $q_{l_1}(t)$ is constant in *current values* in the stationary state and, thus, $q_{l_1}(t) = q_{l_1}^\infty \exp[-\rho t]$ with some constant $q_{l_1}^\infty \geq 0$ in *present values*.

A.7 Proof of Proposition 4

Assume that it is optimal in the long-run stationary state to use the total labor endowment to employ and maintain the capital stock for the new technology, i.e. $l_1^\infty = 0$, $l_2^\infty = \frac{\lambda}{\lambda+\kappa\gamma}$. Then, all output is solely produced by the new technology, i.e. $x^\infty = x_2^\infty = \frac{1}{\lambda+\kappa\gamma}$, $x_1^\infty = l_1^\infty = 0$.

From the demand correspondences (24) and (26) we know that

$$\frac{w(t)}{p(t)} \geq 1 \; , \quad \frac{r(t)}{p(t)} = \frac{1}{\kappa}\left(1 - \lambda\frac{w(t)}{p(t)}\right) \; . \tag{A.31}$$

Solving equation (21a) for q_b and inserting it, together with conditions (A.31), into equation (22) yields for the shadow price of capital:

$$q_k^\infty(t) = \frac{1-\lambda w^\infty}{\kappa(\gamma+\rho_p)} U'(x^\infty)\exp[-\rho_p t] \; , \tag{A.32}$$

where $w^\infty = \frac{w(t)}{p(t)}$ evaluated at the full replacement stationary state, and is thus a constant. Inserting $q_b(t)$ and $q_k^\infty(t+\sigma)$ into equation (21b), we derive the following condition:

$$w^\infty U'(x^\infty)\exp[-\rho_p t] = \frac{1-\lambda w^\infty}{\kappa(\gamma+\rho_p)} U'(x^\infty)\exp[-\rho_p(t+\sigma)] \; . \tag{A.33}$$

Dividing by $\frac{U'(x^\infty)}{\kappa(\gamma+\rho_p)}\exp[-\rho_p(t+\sigma)]$, taking into account that $w^\infty \geq 1$ and rearranging terms yields condition (31).

□

A.8 Proof of Proposition 5

The proof is analogous to the proof of proposition 3. Assume that it is *optimal not to invest* at all times t. As a consequence, the economy will remain in the no investment corner solution where no capital is accumulated. Hence, $i(t) = 0, \; q_i(t) \geq 0 \; \forall\, t$ and the inequality (21d) is binding. All energy is solely produced by the established production technique (i.e. $x^0 = x_1^0 = 1 - a^0, \; x_2^0 = 0$). We know from conditions (33), (34) and (26):

$$1 = \tau_e^0\big(G'(a^0)(1+a^0) + 1 - G(a^0)\big) \; , \tag{A.34a}$$

$$\frac{w(t)}{p(t)} = \tau_e^0 G'(a^0) \; , \tag{A.34b}$$

$$\frac{r(t)}{p(t)} \geq \frac{\tau_e^0\big[(1+a^0-\lambda)G'(a^0) + 1 - G(a^0)\big]}{\kappa} \; . \tag{A.34c}$$

Equation (A.34a) determines the profit maximizing abatement effort a^0 of firm 1. Solving equation (21a) for q_b and inserting, together with conditions (A.34c), in equation (21c) yields the following inequality for the shadow price of capital:

$$q_k^0(t) \geq \frac{\tau_e^0\big[(1+a^0-\lambda)G'(a^0) + 1 - G(a^0)\big]}{\kappa(\gamma+\rho_p)} U'(x^0)\exp[-\rho_p t] \; . \tag{A.35}$$

Inserting equation (A.34b), q_b and q_k^0 into equation (36) and taking into account that $q_i(t) \geq 0$ we derive:

$$\tau_e^0 G'(a^0)U'(x^0) \geq \frac{\tau_e^0\left[(1+a^0-\lambda)G'(a^0)+1-G(a^0)\right]}{\kappa(\gamma+\rho_p)}U'(x^0)\exp[-\rho_p\sigma] - \tau_i^0 U'(x^0) \ . \quad \text{(A.36)}$$

Dividing by $\tau_e^0 G'(a^0)U'(x^0)$ and rearranging terms yields that the *no* investment corner solution is a market equilibrium, iff:

$$\lambda + \left[1 + \frac{\tau_i^0}{\tau_e^0 G'(a^0)}\right]\kappa(\gamma+\rho_p)\exp[\rho_p\sigma] \geq 1 + a^0 + \frac{1-G(a^0)}{G'(a^0)} \ . \quad \text{(A.37)}$$

That, in turn, implies that in the regulated market equilibrium there *is* investment in the new technology, if and only if condition (44) holds.

By setting $\tau_e^0 = \frac{D'(e^0)}{U'(x^0)}$, condition (A.34a) which determines the profit maximizing abatement effort a^0 becomes identical to equation (15) which determines the socially optimal abatement level. Furthermore, inserting τ_e^0 and τ_i^0 from equations (46) and (47) into condition (44) yields (after some tedious calculations) the investment condition in the social optimum (14).

□

A.9 Proof of Proposition 6

Assume that using the total labor endowment to employ and maintain the capital stock for the new technology in the long-run stationary state is a market equilibrium, i.e. $l_1^\infty = 0$, $i^\infty > 0$ and $q_i^\infty = 0$. Then, all output is solely produced by the new technology, i.e.$x^\infty = x_2^\infty = \frac{1}{\lambda+\kappa\gamma}$ and $x_1^\infty = l_1^\infty = 0$. In addition, no emissions are produced and have to be abated and, thus, $e^\infty = 0$ and $a^\infty = 0$. For this case, we know from the demand correspondences (34) and (26) of firm 1 and firm 2:

$$\frac{w(t)}{p(t)} \leq 1 - \frac{\tau_e(t)}{p(t)} \ , \quad \text{(A.38a)}$$

$$\frac{r(t)}{p(t)} = \frac{1}{\kappa}\left(1 - \lambda\frac{w(t)}{p(t)}\right) \ . \quad \text{(A.38b)}$$

Solving equation (21a) for q_b and inserting it, together with condition (A.38b), in equation (21c), yields for the the shadow price of capital:

$$q_k^\infty(t) = \frac{1-\lambda w^\infty}{\kappa(\gamma+\rho_p)}U'(x^\infty)\exp[-\rho_p t] \ , \quad \text{(A.39)}$$

where $w^\infty = \frac{w(t)}{p(t)}$ evaluated at the full replacement stationary state and thus is a constant.

Inserting q_b, q_k and inequality (A.38a) into equation (36), and taking into account that $q_i(t) = 0$, we derive the following condition:

$$(1-\tau_e^\infty)(\lambda + \kappa(\gamma+\rho_p)\exp[\rho_p\sigma]) \leq 1 - \tau_i^\infty\kappa(\gamma+\rho_p)\exp[\rho_p\sigma] \ . \quad \text{(A.40)}$$

Dividing by $(1-\tau_e^\infty)$ and rearranging terms yields condition (48).

Furthermore, inserting τ_e^∞ and τ_i^∞ from equations (49) and (50) into condition (48) yields (after some tedious calculations) the full replacement condition in the social optimum (16).

□

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