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Enforcement of Intellectual Property, Pollution Abatement, and Directed Technical Change

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Abstract We theoretically investigate the interaction between endogenous enforcement of intellectual property rights (IPRs) and tax-financed pollution abatement measures. IPRs affect dirty and clean intermediates alike such that higher IPR enforcement may promote the transition to the clean technology, if this technology is productive enough. If the green technology is relatively unproductive, higher IPRs promote the dirty technology while pollution is increasing. As households are due to subsistence consumption subject to a hierarchy of needs, the level of IPR enforcement as well as the level of abatement measures depends on the state of technology and is increasing during economic development. Thus, if the incentive to enforce IPRs is low the level of abatement measures is also low. This argument provides a theoretical foundation for the observed clash of interests in international negotiation rounds regarding the harmonization of IPR protection and actions to combat climate change.

Keywords Directed technical change · Intellectual property rights · Pollution

JEL Classification O30 · O33 · O34 · Q53 · Q54 · Q56 · Q58

1 Introduction

The question of how to reconcile the restrictions of the climate system with sustained economic growth in the standards of living constitutes across the globe a major challenge for societies at large. In order to resolve the tension between economic growth and pollution,

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existing literature suggests a redirection of innovations from dirty to clean technologies rather than a stall of economic growth. Moreover, the adverse impact of production on the environment may be dampened by appropriate economic policies like pollution taxes, permits or tax-financed abatement measures.

A growing body of empirical evidence implies that the transition to clean technologies may occur in response to policies and changes in prices that affect the relative profitability of clean and dirty technologies. For example, Popp (2002) finds that higher energy prices are associated with an increase in energy-saving innovations. Bretschger (2015) states that decreasing energy input and increasing energy prices induce additional investments fostering long-run growth while the growth effect counteracts the negative static effects of lower energy use. Aghion et al. (2016) expose that carbon taxes affect the direction of innovations in the automobile industry. Moreover, they provide evidence for some path-dependency of green innovations. These findings support the arguments brought forward by models of directed technical change in spirit of Acemoglu (1998, 2002) which have been applied to environmental aspects for example by di Maria and Smulders (2004), di Maria and Valente (2008), Acemoglu et al. (2012), Schäfer (2014), and van der Meijden and Smulders (2014)—for a comprehensive but probably still incomplete list.[1]

Consequently, the transition from dirty to clean technologies requires economic polices that promote incentives to engage in green R&D activities. In general, the literature discusses against this background the role of taxes and subsidies while in most endogenous growth models, patent protection and the enforcement of patents is taken for granted.

In this paper, we argue within a framework of directed technical change in the spirit of Acemoglu et al. (2012) that there exists a reenforcing interaction between the incentives to enforce intellectual property rights (IPRs) and the willingness to pay for tax-financed abatement measures. Moreover, the incentives to enforce IPRs and the willingness to pay for tax-financed abatement measures are affected by the stage of economic development. We take thus a development economic perspective, in the sense that the economy surpasses a hierarchy of needs characterized by relatively high expenditure shares on current consumption when disposable incomes are comparatively low. Earlier stages of economic development are, therefore, characterized by low savings, thus low investments in R&D, low enforcement levels of IPRs and a low willingness to pay for tax-financed pollution abatement measures. This argument provides a theoretical foundation for the observed clash of interests in international negotiation rounds regarding the harmonization of IPR protection and actions to combat climate change. We illustrate this argument in Fig. 1. There, we present the evolution of local pollutants captured by PM2.5 between 1990 and 2013 in the OECD and a selected group of (fast) developing countries.[2] Since 2009, the latter has been accused, repetitively, by the European Commission for severe copyright infringements.[3] As the figure shows, in these countries the concentration of local pollutants is above the level of the OECD countries and

[1] For more empirical findings see Acemoglu et al. (2016). In contrast to the above mentioned literature, Bretschger and Smulders (2012) find that poor input substitution need not be detrimental for sustainable growth. Our framework is based like the other directed technical change frameworks on comparatively high elasticities of substitution. The requirement of high elasticities of substitution between clean and dirty inputs will be discussed further below, see ftn. 19.

[2] Although we present in Fig. 1 the evolution of local pollutants, it is evident that a low willingness to pay for abatement measures at the local level translates due to free-rider incentives into an even lower willingness to pay at the global level.

[3] See for example the European Commission's IPR Enforcement Report 2009 and the European Commission's Report on EU Customs Enforcement of Intellectual Property Rights 2014.

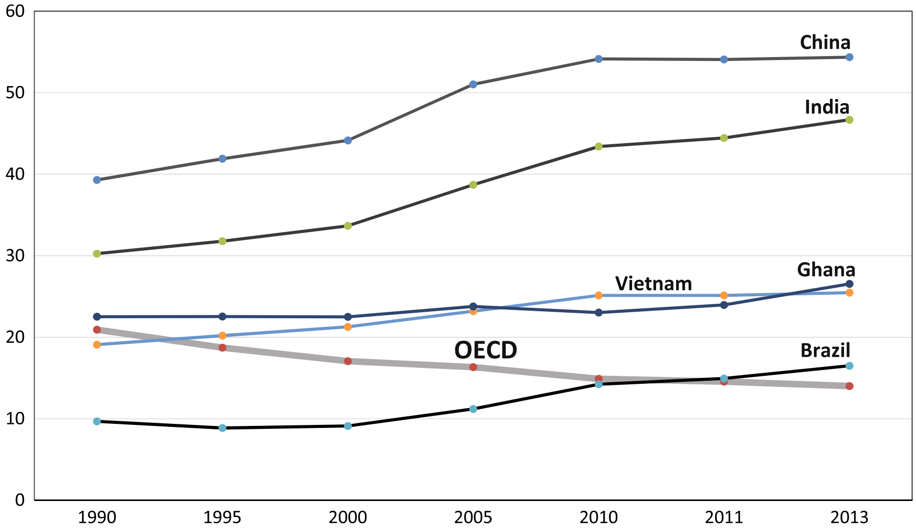

Fig. 1 PM2.5 air pollution, mean annual exposure (micrograms per cubic meter); *Source*: World Development Indicators 2016

characterized by an increasing trend while the OECD is characterized by a declining trend. Our theory suggests a hierarchy of needs as the driving mechanism behind this observation.

As regards the enforcement of intellectual property rights, we build on Schäfer and Schneider (2015). The difference is that we consider a fully dynamic general equilibrium framework with directed technical change and an environmental externality, but abstract from international trade and international negotiations of IPR enforcement levels, i.e. we consider a closed economy. By doing so, we pay special attention to the enforcement of IPRs rather than different patent legislations. We consider this as the more relevant issue since the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPs) specifies a minimum set of protection standards that members of the World Trade Organization (WTO) have to assent to, but the enforcement of intellectual property rights is still subject to great international heterogeneity. For example, the European Commission's IPR Enforcement Report 2009 gives account of serious problems with IPR enforcement in a large number of mostly developing countries. Among those are the countries which are depicted in Fig. 1. Complaints include injunctions or criminal sanctions often being difficult to obtain and civil procedures being lengthy and burdensome with high uncertainty of outcomes. Involved staff is insufficiently trained and lacks resources to effectively prosecute and convict violators, and cooperation between authorities is insufficient. For some countries the report even assesses a lack of political will indicated by their opposing in-depth enforcement discussions in international fora such as the WTO or the WIPO.[4]

Our analysis regarding the enforcement of IPRs is characterized by the following features: First, we assume equal strength of enforcement of all active patents at any point in time. Second, a government cannot commit to IPR enforcement for the indefinite future and its planning horizon is limited. By this assumptions, we intend to capture important aspects of

[4] See EU Commission (2009). A similar picture is drawn in the annual Special 301 Reports by the U.S. Trade Representative; see Office of U.S. Trade Representative (2010). Recently, the OECD estimated the value of counterfeited products in foreign trade in 2007 as around $270 billion (OECD 2009). For further details, see Schäfer and Steger (2014).

IPR enforcement. With regard to the first item, we argue that in reality IPR enforcement depends on whether or not a patent is active, ruling out the possibility that IPR enforcement distinguishes active patents by, e.g., the year of invention. Second, although formal law may be fixed for substantial time horizons, the enforcement of laws can be changed more easily for example, by reallocating resources used for IPR enforcement to other purposes. This captures the emergence of heterogeneities in terms of IPR-enforcement levels described above.[5]

In most endogenous growth models, patent protection and the enforcement of patents is taken for granted. Workhorse models of endogenous growth typically even assume a infinite patent length. A seminal work in the literature on intellectual property rights protection is Grossman and Lai (2004), which employs a framework of variety expanding innovations, but considers a one-shot game with respect to IPR-protection and does not allow for endogenous long-run economic growth. The equilibrium in Grossman and Lai (2004) can be interpreted as a subgame-perfect Nash-equilibrium, where governments are able (1) to decide on the IPR-protection level of each vintage of inventions separately and (2) to fully commit to it in the future. Such a set-up implies the theoretical possibility that at a particular point in time, all different vintages of active patents enjoy different levels of IPR-enforcement. This is precluded in our model.[6] At the heart of the framework, we present here, is the governments' classical trade-off between static efficiency and dynamic gains of IPR-protection with regard to R&D incentives and profit flows.[7] By choosing IPR-enforcement, the government has to trade off welfare today—by incurring deadweight losses and R&D costs—against future welfare resulting from a higher technological level. Without internalizing the full future benefits of innovations, an office-term motivated government may be more reluctant to bear the costs of great innovative activity implying a substantial burden on current welfare.[8]

The decision about the level of tax-financed abatement measures takes the choice of IPR enforcement as given and is also subject to a limited planning horizon.[9] This assumption is based on the observation that the roots of the present patent legislation dates back to the 14th century.

[5] This means that we account for the observed harmonization in the international patent legislation due to TRIPS but still substantial heterogeneity in terms of enforcement levels of the same laws on the national level. We then argue that the state of development of the economy is decisive for the preferred level of IPR enforcement capturing the observed heterogeneity depicted in Fig. 1.

[6] The major difference is that in Grossman and Lai (2004), the policy maker determines in each period of time the level of IPR-protection only for the products invented in the same period but for the duration of their entire lifetime (i.e. until the products become obsolete). In our model, the policy maker decides in each period on the level of IPR-enforcement of all products under de-jure IPR-protection but cannot commit to enforcement levels in future periods.

[7] These arguments date back to Nordhaus (1969).

[8] The literature has approached questions regarding the protection of IPR from two perspectives. On the one hand, from a macroeconomic, endogenous growth perspective which treats the IPR-enforcement as exogenous and examines its effects on the resulting growth rate and on welfare (Helpman 1993; Lai 1998; Kwan and Lai 2003; Iwaisako et al. 2011). On the other hand, from a rather microeconomic, industrial organization perspective that explicitly takes IPR-enforcement as endogenous, but precludes long-run dynamics (Chin and Grossman 1990; Deardorff 1992; Maskus 1990; Diwan and Rodrik 1991; Lai and Qiu 2003). An intriguing paper by Eicher and Garcia-Penalosa (2008) takes a complementary approach to endogenizing the strength of IPR-enforcement in an endogenous growth model of a closed economy. Rather than being a policy instrument of the government, IPR enforcement is the result of private investments by firms. This leads to multiple equilibria (one with high (low) IPR-enforcement and high (low) R&D investments) as investments in IPR-protection and investments in R&D are complements.

[9] For the implementation of pollution externalities into dynamic general equilibrium models, see for example Xepapadeas (2005).

Incorporating these features into a dynamic model with directed technical change arguably makes the analysis of IPR enforcement more realistic. However, it is also particularly interesting because it helps to understand the tensions between advanced and developing countries as captured by Fig. 1. The enforcement of IPRs benefits clean and dirty technologies alike, while a pollution externality stemming from the use of dirty intermediates adversely affects total factor productivities and the incentive to enforce IPRs. To the contrary, pollution abatement measures reduce disposable incomes and thus investment in R&D, but increase total factor productivity in subsequent periods and provide thus higher incentives to enforce IPRs in the future. Since agents are subject to a hierarchy of needs, in the sense that the savings rate is increasing in incomes, the incentive to enforce IPRs and to implement tax-financed abatement measures depends on the stage of technological knowledge. This mechanism is particularly important for the understanding and recognition of obstacles faced by developing countries during a transition to clean production technologies or the implementation of tax-financed pollution abatement measures.[10]

The remainder of the paper is organized as follows: In Sect. 2, we introduce the model, where 2.1 contains the overlapping-generations (OLG) structure of households and 2.2 the production side of the model. In Sect. 3, we describe the equilibrium structure. The policy instruments, enforcement of IPRs and tax-financed abatement measures are discussed in Sect. 4. In Sect. 5, we discuss several aspects and implications of our paper. Finally, Sect. 6 provides a summary and concludes.

2 The Model

2.1 Households

In this setting time is discrete and indexed by $t = 1, 2, \ldots, \infty$. In each period, t, our economy is populated by a [0, 1]-continuum of households, i.e. we abstract from population growth and population size is normalized to one. Each individual lives for two periods: adulthood and old-age. Agents' time endowment is normalized to one. Each agent supplies during adulthood one unit of labor inelastically to the labor market and earns w_t. Moreover, a representative agent consumes c_t and saves the amount s_t in order to cover old-age consumption, c_{t+1}, during retirement in the second and last period of life. Lifetime utility of a representative agent is specified as

$$u_t = \begin{cases} \frac{(c_t-\bar{c})^{1-\theta}-1}{1-\theta} + \beta\frac{c_{t+1}^{1-\theta}-1}{1-\theta}, & \text{if } \theta > 0, \theta \neq 1 \\ \ln(c_t - \bar{c}) + \beta\ln(c_{t+1}), & \text{if } \theta = 1 \end{cases} \tag{1}$$

with $\bar{c} \geq 0$ denoting subsistence consumption, $0 < \beta < 1$ representing the discount factor of future consumption and θ the inverse of the intertemporal elasticity of substitution.

As usual, the log-linear specification of lifetime utility assures analytical tractability within an OLG framework. If, however, $\bar{c} > 0$ this assumption is not as restrictive as in the canonical version of the OLG-model since the intertemporal elasticity of substitution is not constant and the savings rate is increasing in income. In other words: $\bar{c} > 0$ introduces a hierarchy of needs into the utility function. Increasing incomes lower the importance of expenditures on

[10] These results complement to some extent the findings by Bretschger and Suphaphiphat (2014) in that a pure development aid strategy would also in our case not necessarily induce a transition to the clean technology but it may help to implement at least tax-financed abatement measures.

first-period consumption and increase savings. In order to shed light onto certain mechanisms, we will occasionally reduce the model to the case where $\bar{c} = 0$.

Denoting the gross-interest rate by R_{t+1}, the budget constraint of a representative households reads

$$w_t = c_t + s_t, \tag{2}$$

with $s_t R_{t+1} = c_{t+1}$, such that the present value of lifetime expenditures equals lifetime earnings, i.e. $w_t = c_t + \frac{c_{t+1}}{R_{t+1}}$.

Maximizing (1) subject to (2) yields

$$c_t = \begin{cases} \frac{1}{1+\beta^{\frac{1}{\theta}} R_{t+1}^{\frac{1-\theta}{\theta}}} \left[w_t + \beta^{\frac{1}{\theta}} R_{t+1}^{\frac{1-\theta}{\theta}} \bar{c} \right], & \text{if } \theta > 0, \theta \neq 1, \\ \frac{w_t}{1+\beta} + \frac{\beta}{1+\beta} \bar{c}, & \text{if } \theta = 1, \end{cases} \tag{3}$$

$$\frac{c_{t+1}}{R_{t+1}} = \begin{cases} \frac{\beta^{\frac{1}{\theta}} R_{t+1}^{\frac{1-\theta}{\theta}}}{1+\beta^{\frac{1}{\theta}} R_{t+1}^{\frac{1-\theta}{\theta}}} [w_t - \bar{c}], & \text{if } \theta > 0, \theta \neq 1 \\ \frac{\beta}{1+\beta} (w_t - \bar{c}), & \text{if } \theta = 1. \end{cases} \tag{4}$$

It is important to emphasize here, that we don't distinguish the cases $\theta = 1$ and $\theta \neq 1$ for the sake of academic completeness, but this distinction becomes important for the subsequent analysis, such that it would not suffice to restrict the analysis to $\theta = 1$ as it is usually done in the literature. Nevertheless, the benchmark case $\theta = 1$ serves as a theoretical point of reference for the derivation of analytical results in the more general case which we could not discern analytically, otherwise.

2.2 IPRs, Production and R&D

Intellectual Property Rights Our analysis builds on a variety-expanding-growth framework of the Romer (1990)-type where in period t a patent is enforced with probability ν_t. For simplicity, we assume that imitation is costless.[11] Thus, if the patent is not enforced in period t, an imitated intermediate good is supplied under full competition and operating profits are zero. This modeling strategy reflects our focus on IPR-enforcement, in the sense that we emphasize the importance of prosecuting patent infringements.[12] Since, we consider a two period OLG model where one period encompasses around thirty years and the average patent length is in reality around 20 years, ν_t can be interpreted as the average enforcement level of IPR protection within a typical period t. Simplifying matters, we assume that a patent holds for one period, i.e. one generation and therefore a little longer than observed lifespans. Taking this at face value, in a set-up where the lifespan of a patent is split up into more periods, in the sense that a typical period t consists of $t_1, \ldots, t_{30}$ years, a patent holder may earn monopoly profits in year t_1 and t_3 but enforcement fails in year t_2, such that over the lifespan of a patent of around 30 years, ν_t represents the adjusted probability over the typical period that a certain patent will be enforced.[13]

[11] The implementation of imitation costs would not alter our results.

[12] This follows Schäfer and Schneider (2015) and contrasts with earlier papers by Helpman (1993) and Lai (1998).

[13] For more details, see Schäfer and Schneider (2015).

A patent holder may produce the same monopolistic quantity of the intermediate product in each period but can only charge the monopoly price in the periods where IPR-enforcement is perfect. In the period without enforcement of IPRs, other competitors are not effectively deterred from offering the intermediate good as well (after reverse-engineering it), thereby driving down prices to marginal costs. A broader interpretation is that different degrees of IPR-enforcement constrain the degree of competition from violators of IPRs, thereby determining the (oligopolistic) prices that the patent-holders are able to charge. Then the strength of IPR-enforcement $\nu_{j,t}$ reflects the share of the monopoly profits that can be captured in period t.[14]

Moreover, the patent will be sold in $t+1$ at the competitive price to someone chosen randomly from the then young generation. This assumption follows Aghion and Howitt (2009, Ch. 4) and avoids tedious intertemporal pricing and related dynastic problems while the incentive to engage in R&D remains untouched.[15]

We now introduce the model for given levels of IPR-enforcement, ν_t, and discuss the governments' problem concerning their IPR-enforcement choice further below.

Final Output In period t there is a unique final good, Y_t, that can be consumed or saved. Moreover, Y_t, is produced by a large number of fully competitive firms using dirty and clean intermediates as inputs, which are denoted by $Y_j,\ j = c, d$. Y_t is produced according to the following CES-production function

$$Y_t = P_t^{-\gamma}\left(Y_{c,t}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{d,t}^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{5}$$

with $\gamma > 0$ and $\varepsilon \in (0, \infty)$ determining the elasticity of substitution between clean and dirty inputs.

Pollution P_t denotes the pollution stock in period t which adversely affects the productivity of factors of production.[16] Pollution is generated by emissions, E_t, stemming from the use of dirty intermediates in final output production, i.e. $E_t = Y_{d,t}$. Emissions in turn may be reduced by tax-financed abatement measures, $M_t \geq 0$. The emergence of abatement measures is endogenous in our setting and will be introduced further below. For the dynamics of the pollution stock we assume a standard and simple accumulation law

$$P_{t+1} = (1-\eta)P_t + Y_d(1+M_t)^{-1}, \quad \eta \in [0, 1], \tag{6}$$

where η represents the absorptive capacity of the environment with respect to pollutants. Moreover, $P_{t+1} = \bar{P}_{min}$, if $Y_d < Y_d^{crit} \geq 0$.[17] Finally, this formulation allows for $M_t = 0$.

[14] This could be incorporated explicitly by a model with oligopolistic competition, where the patent holder competes with one or several imitators. However, our modeling approach captures the essence of declining expected profits for the patent holder when IPR-enforcement becomes weaker, and it avoids tedious calculations implied by a set-up with oligopolistic competition.

[15] Moreover, we assume as Strulik et al. (2013) that the revenues are spent unproductively on public consumption. We could also assume that machines are sold after period $t+1$ at the competitive price equal to 1. This would however complicate the notation. Alternatively, we could assume complete depreciation of technological knowledge after one period arguing that knowledge about the steam engine should become obsolete after some time, see Schäfer (2014), which has related to the process of knowledge creation, however, other shortcomings.

[16] This formulation builds for example on Smulders and Gradus (1995) and many others. We could also introduce environmental quality into agents' utility function, but this would not affect our results qualitatively. For applications in an OLG context, see for example Mariani et al. (2010), inspired by John and Pecchenino (1994) or Varvarigos (2010).

[17] There is always some pollution in the ecosystem, such that environmental quality does not approach infinity. We did not model environmental quality explicitly in order to save on notation which obviously does not affect any of our results, see Xepapadeas (2005).

Clean and dirty Intermediates Intermediates, $Y_{j,t}$, are produced with labor, $L_{j,t}$, and a range of horizontally differentiated machines, $x_{j,t}(i)$

$$Y_{j,t} = AL_{j,t}^{1-\alpha} \int_0^{N_{j,t}} x_{j,t}(i)^\alpha di, \tag{7}$$

where $A > 0$ is a productivity parameter and $\alpha \in (0, 1)$ determines the elasticity of substitution between two different types of machines.

The production of one unit of $x_{j,t}(i)$ requires one unit of final output. Furthermore, we choose final output as numeraire such that marginal production cost of machines is equal to unity. Given the enforcement level $0 \leq \nu_t \leq 1$, the number of protected intermediates in sector j, at time t is $\nu_t * N_{j,t}$, while $(1 - \nu_t) * N_{j,t}$ of the intermediates are imitated. Thus output in sector j writes as

$$Y_{j,t} = AL_{j,t}^{1-\alpha} \left[\int_0^{\nu_t N_{j,t}} [x_{m,j,t}(i)]^\alpha di + \int_0^{(1-\nu_t)N_{j,t}} [x_{c,j,t}(i)]^\alpha di \right]. \tag{8}$$

Research and Development R&D constitutes the search for new designs (blueprints) of machines. To this end, research firms rent labor services and machines, while taking the current level of technological knowledge as given. Since the process of knowledge creation is not the primary objective of this paper, we keep matters as simple as possible and assume that labor and machines combine to produce blueprints in exactly the same way that they combine to produce final output, i.e. we apply the so-called lab equipment approach

$$N_{j,t+1} = \left(1 + \gamma_j \frac{D_{j,t}}{N_{j,t}}\right) N_{j,t}, \tag{9}$$

where $\gamma_j > 0$ denotes a productivity parameter and $D_{j,t} \geq 0$ represents spending on R&D in units of the final good. $N_{j,t+1}$ reflects the level of technological knowledge captured by the number of differentiated intermediates, i.e. the number of patented intermediates.

3 Equilibrium

In case a patent is enforced, machine producers earn profits $\pi_{m,j,t}(i) = (p_{m,j,t}(i) - 1) x_{m,j,t}(i) > 0$ and $\pi_{c,j,t}(i) = 0$ otherwise. The standard implications of a symmetric equilibrium imply that $p_{m,j,t}(i) = p_{m,j,t} = 1/\alpha$ and $p_{c,j,t}(i) = p_{c,j,t} = 1$. Moreover, profit maximization of intermediate producers implies the following demand functions for machines

$$x_{m,j,t}(i) = x_{m,j,t} = \alpha^{\frac{2}{1-\alpha}} (p_{j,t}A)^{\frac{1}{1-\alpha}} L_{j,t}, \tag{10}$$

$$x_{c,j,t}(i) = x_{c,j,t} = \alpha^{\frac{1}{1-\alpha}} (p_{j,t}A)^{\frac{1}{1-\alpha}} L_{j,t}, \tag{11}$$

such that

$$\pi_{m,j,t} = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} (p_{j,t}A)^{\frac{1}{1-\alpha}} L_{j,t}. \tag{12}$$

Observing that $x_{m,j,t} = \alpha^{\frac{1}{1-\alpha}} x_{c,j,t}$, the level of intermediate $Y_{j,t}$ writes as

$$Y_{j,t} = p_{j,t}^{\frac{\alpha}{1-\alpha}} A^{\frac{1}{1-\alpha}} L_{j,t} N_{j,t} \left[1 + \nu_t \left(\alpha^{\frac{\alpha}{1-\alpha}} - 1\right)\right]. \tag{13}$$

Regarding the effect of IPR-enforcement on the level of $Y_{j,t}$ two observations are worth being noticed: (1) $\nu_t (\alpha^{\frac{\alpha}{1-\alpha}} - 1) < 0$ represents the deadweight loss due to monopoly pricing which is apparently increasing in the enforcement level of IPR protection. (2) For $\nu_t = 1$ we obtain the standard Romer (1990) case and for $\nu_t = 0$ the highest possible output from a static point of view, but obviously $\nu_t = 0$ would undermine incentives to invest in R&D. Thus, when deciding about the optimal level of IPR enforcement, the government has to balance the marginal benefit of an additional blueprint against an increase in deadweight losses. This constitutes the central trade-off between static losses and dynamic gains when it comes to the enforcement of IPRs.[18] We come back to this point further below.

Noting that the price index of final output, $p_{Y,t}$, is given as $P_t^{\gamma}\left(p_{c,t}^{1-\varepsilon} + p_{d,t}^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} = p_{Y,t} \equiv 1$, we obtain

$$p_{c,t} = P_t^{-\gamma}\left[1 + \left(\frac{p_{d,t}}{p_{c,t}}\right)^{1-\varepsilon}\right]^{\frac{1}{\varepsilon-1}}, \tag{14}$$

$$p_{d,t} = P_t^{-\gamma}\left[1 + \left(\frac{p_{c,t}}{p_{d,t}}\right)^{1-\varepsilon}\right]^{\frac{1}{\varepsilon-1}}, \tag{15}$$

such that demand for machines, profits and the level of intermediates in both sectors is adversely affected by the pollution level in t.

Perfect mobility of labor between sectors implies $p_{c,t}\frac{Y_{c,t}}{L_{c,t}} = p_{d,t}\frac{Y_{d,t}}{L_{d,t}}$, such that in light of the resource constraint, $L_{c,t} + L_{d,t} = 1$, employment levels write as

$$L_{c,t} = \frac{1}{1 + \left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}, \tag{16}$$

$$L_{d,t} = \frac{\left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}{1 + \left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}, \tag{17}$$

with $\sigma = (1-\alpha)(1-\varepsilon)$.

Throughout this paper, we assume that $\varepsilon > 1$, such that $\sigma < 0$, which implies that the two intermediates are gross-substitutes.[19] Furthermore, the emergence of directed technical change is assured. Combining now (13), with (14–17) yields the equilibrium level of clean and dirty intermediates

$$Y_{c,t} = (AP_t^{-\alpha\gamma})^{\frac{1}{1-\alpha}}\left[N_{c,t}^{\sigma} + N_{d,t}^{\sigma}\right]^{-\frac{\alpha+\sigma}{\sigma}} N_{d,t}^{\alpha+\sigma} N_{c,t}[1 + \nu_t\Psi_D], \tag{18}$$

$$Y_{d,t} = (AP_t^{-\alpha\gamma})^{\frac{1}{1-\alpha}}\left[N_{c,t}^{\sigma} + N_{d,t}^{\sigma}\right]^{-\frac{\alpha+\sigma}{\sigma}} N_{c,t}^{\alpha+\sigma} N_{d,t}[1 + \nu_t\Psi_D], \tag{19}$$

[18] See Nordhaus (1969). Obviously, in reality costs of IPR enforcement exceed deadweight losses since a sophisticated prosecution of patent infringements requires skilled labor in terms of lawyers, judges, and engineers but the implementation of this aspects only increases the structural complexity of the model without delivering further insights, such that we reduce the model to the described trade-off.

[19] Acemoglu et al.(2012, p. 135) state: "The degree of substitution, which plays a central role in the model, has a clear empirical counterpart. For example, renewable energy, provided it can be stored and transported efficiently, would be highly substitutable with energy derived from fossil fuels. This reasoning would suggest a (very) high degree of substitution between dirty and clean inputs, since the same production services can be obtained from alternative energy with less pollution". and "in fact, an elasticity of substitution significantly greater than 1 appears as the more empirically relevant benchmark, since we would expect successful clean technologies to substitute for the functions of dirty technologies. For this reason, throughout the article we assume that $\varepsilon > 1 \ldots$". Obviously, a high degree of substitution requires the technical solution of several problems related to the storage and transportation of highly volatile renewables. This argument raises indeed concerns. Nevertheless, Papageorgiou et al. (2016) provide the first systematic estimation using data in a panel of 26 countries concluding that ε exceeds one. I am grateful to Tunc Durmaz for pointing this out to me.

implying that the level of final output writes as

$$Y_t = (AP_t^{-\gamma})^{\frac{1}{1-\alpha}} \left[N_{c,t}^{\sigma} + N_{d,t}^{\sigma} \right]^{-\frac{1}{\sigma}} [1 + \nu_t \Psi_D], \tag{20}$$

with $\Psi_D = (\alpha^{\frac{\alpha}{1-\alpha}} - 1) < 0$ representing the deadweight loss factor due to monopolistic distortions.

Free entry in R&D drives expected profits of research labs down to zero in both sectors, such that the zero profit condition implies

$$\frac{E[\pi_{j,t+1}]}{R_{t+1}} = \frac{\nu_{t+1}\pi_{m,j,t+1}}{R_{t+1}} = 1. \tag{21}$$

Hence, in the presence of R&D activities in both sectors the following non-arbitrage condition must hold

$$\frac{\gamma_c}{\gamma_d} \left(\frac{\left(1 + \gamma_c \frac{d_{c,t} S_t}{N_{c,t}}\right) N_{c,t}}{\left(1 + \gamma_d \frac{(1-d_{dc,t}) S_t}{N_{d,t}}\right) N_{d,t}} \right)^{-1-\sigma} = 1, \tag{22}$$

with $d_{j,t} S_t = D_{j,t}$ and $d_{c,t} + d_{d,t} = 1$, such that we obtain from the last expression the share of savings allocated to clean R&D as

$$d_{c,t} = \frac{\tilde{\gamma}^{\frac{1}{1+\sigma}} \left(1 + \gamma_d \frac{S_t}{N_{d,t}}\right) - \frac{N_{c,t}}{N_{d,t}}}{\left(\gamma_c + \tilde{\gamma}^{\frac{1}{1+\sigma}} \gamma_d\right) \frac{S_t}{N_{d,t}}}, \tag{23}$$

with $\tilde{\gamma} = \frac{\gamma_c}{\gamma_d}$ and $d_{d,t} = 1 - d_{c,t}$, while aggregate savings are in light of (4) and due to the normalization of population size to 1 equal to $\frac{c_{t+1}}{R_{t+1}}$. The following proposition summarizes the long-run characteristics of the economy with respect to its productivity growth rate and the allocation of resources ($d_{j,t}$) to R&D.

Proposition 1 (i) *If both, the clean and the dirty technology are used, the long-run growth rate of innovations reads as*

$$g_*^{N_c} = g_*^{N_d} = g_* = \frac{\gamma_d \gamma_c \frac{S_t}{N_{d,t}}}{\gamma_c + \gamma_d \tilde{\gamma}^{\frac{1}{1+\sigma}}}. \tag{24}$$

If only one technology is active: $g_* = \gamma_j \frac{S_t}{N_{j,t}}$.

(ii) *An increase in (aggregate) savings generated by an increase in wages, or profits in case that* $\theta < 1$, *induce an increase in the share of R&D expenditures for clean technologies, if*

$$\frac{\partial d_{c,t}}{\partial S_t} = \frac{\left(N_{c,t} - \tilde{\gamma}^{\frac{1}{1+\sigma}} N_{d,t}\right)}{\left(\tilde{\gamma}^{\frac{1}{1+\sigma}} + \gamma_c\right) S_t^2} > 0. \tag{25}$$

Obviously $\frac{\partial d_{c,t}}{\partial S_t} > 0$, if $N_{c,t} - \tilde{\gamma}^{\frac{1}{1+\sigma}} N_{d,t} > 0$. Thus an increase in available resources allocated to R&D captured by aggregate savings (S_t) induces an increase in the share of spending directed to green R&D ($d_{c,t}$) only, if the clean sector is characterized by sufficiently high technological knowledge in comparison to the dirty sector. Moreover, (22) is increasing in $d_{c,t}$, if $1 + \sigma < 0$. Thus analogous to Acemoglu et al. (2012), there are three equilibria: (i) $d_{c,t} = 1$, if for $d_{c,t} = 1$ the left-hand side of (22) is larger or equal than 1, (ii) $d_{c,t} = 0$, if the left-hand side is smaller than 1, and (iii) the interior equilibrium with both R&D sectors being active, i.e. $0 < d_{c,t} < 1$ which is captured by (22).

Finally, we obtain the gross interest rate from the zero profit condition of research labs (21) and the technology market clearing condition (22) together with (12) as

$$\nu_{t+1}\gamma_c(1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}}(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}})^{-\frac{1+\sigma}{\sigma}} = R_{t+1}. \tag{26}$$

Moreover, the wage rate, w_t, reads as

$$w_t = (1-\alpha)Y_t. \tag{27}$$

4 Enforcement of IPRs and Pollution Abatement

4.1 The Government

In a typical period t, the government observes the equilibrium of the economy as well as households decisions (3) and (4). Moreover, the government takes as given the state of the technology $(N_{j,t})$ the pollution stock (P_t) and the level of IPR-enforcement (ν_t). Realistically, we assume that the state has a limited planning horizon. This means that the state is only able to commit credibly to an enforcement level of IPRs and a level of tax-financed abatement measures for the subsequent period. It neglects entirely the consequences of its actions on subsequent periods.[20] Since, the historical roots of national patent legislations date back to the 14th century, we assume that the state decides first about the level of IPR enforcement and then about the level of abatement measures given the decision about ν_{t+1}. The state's limited planning horizon implies that it maximizes utility of the current adult generation and income above subsistence needs of the next young generation in $t+1$. Thus, the objective function of the state is specified as

$$V_t^G = u_t + \rho v(w_{t+1} - \bar{c}), \tag{28}$$ [21]

where $0 \le \rho \le 1$ represents a social discount factor and u_t is given by (1). Noting households decisions (3) and (4), V_t^G writes as

$$V_t^G = (1+\beta)\ln[(1-\tau_t)w_t - \bar{c}] + \rho\ln(w_{t+1} - \bar{c})] + \beta\ln(R_{t+1}) + \Omega, \quad \text{if } \theta = 1, \tag{29}$$

with $\Omega = \beta\ln\beta - (1+\beta)\ln(1+\beta)$, and w_t, w_{t+1},R_{t+1} determined by (26) and (27), and

$$V_t^G = \frac{1}{1-\theta}\left(\frac{1+\beta^{\frac{1+\theta}{\theta}}R_{t+1}^{\frac{1}{\theta}}}{1+\beta^{\frac{1}{\theta}}R_{t+1}^{\frac{1-\theta}{\theta}}}\right)^{1-\theta}(w_t - \bar{c})^{1-\theta} + \rho\frac{(w_{t+1}-\bar{c})^{1-\theta}-1}{1-\theta} - \frac{1+\beta}{1-\theta}, \tag{30}$$

if $\theta > 0$ and $\theta \neq 1$.

[20] As has been noted above, we assume perfect commitment of IPR enforcement for one period. If we would abstract from this assumption, we would allow for hold-up issues and time inconsistencies which are certainly interesting but not the focus of this work. Moreover, note that lack of commitment issues could be solved by Trigger strategies. But even this would open room for a plenitude of (sub-game perfect) equilibria.

[21] We omit u_{t-1} of the current old generation since the stocks and thus u_{t-1} cannot be influenced by available policy instruments in period t.

4.2 Enforcement of IPRs

In this section, we analytically explore the central trade-offs which the state faces when deciding about an optimal enforcement level of IPRs for period $t+1$. In order to assure analytical tractability, we assume for the moment that $\theta = 1$ and discuss the implications for the more general case thereafter. In addition, we set for the same reason $\eta = 1$ which does not affect the analytical results qualitatively, though. The following proposition presents the government's preferred level of IPR-enforcement.

Proposition 2 *Given the evolution of the pollution stock (6), the gross interest rate (26), wages (27) and the current level of IPR-enforcement,* ν_t*, maximization of (29) with respect to* ν_{t+1} *yields*

(i) If $\bar{c} > 0$*:*

$$\nu_{t+1} = \frac{\beta\left[1-\alpha-\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c}\right]}{\Psi_D(\alpha-1)[(1+\rho)\beta+\rho]}, \tag{31}$$

such that for economically meaningful solutions:

a) $\nu_{t+1} = 0$*, if* $1-\alpha-\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c} < 0$ *because* $\Psi_D < 0$ *and* $\alpha < 1$*,*

b) $\nu_{t+1} = 1$*, if* $\frac{\beta\left[1-\alpha-\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c}\right]}{\Psi_D(\alpha-1)[(1+\rho)\beta+\rho]} \geq 1.$

(ii) If $\bar{c} = 0$*: the level of IPR-enforcement is constant and the same for all periods*

$$\nu_{t+1} = \nu_* = -\frac{\beta}{\Psi_D[(1+\rho)\beta+\rho]} > 0, \tag{32}$$

because $\Psi_D < 0$*. Moreover,* $\nu_* = 1$*, if* $-\frac{\beta}{\Psi_D[(1+\rho)\beta+\rho]} \geq 1.$

Several points are worth noting at this stage. (1) If there are no subsistence needs in consumption ($\bar{c} = 0$), the government opts for a constant and positive level of IPR-enforcement, see item (ii) of Proposition 2. The long-run level of IPR enforcement is increasing in β since this imposes a higher weight on capital incomes in V_t^G. If ρ increases, in turn, next period's reduction in wages due to deadweight losses gains in weight which reduces the incentive to enforce IPRs. (2) In the presence of subsistence needs ($\bar{c} > 0$), see item (i), the government's preferred IPR-enforcement level for the subsequent period depends positively on the next period's state of technological knowledge ($N_{j,t+1}$) and total factor productivity (A) but adversely on the pollution stock (P_{t+1}). While $N_{j,t+1}$ and A increase incomes and reduce thus the weight of subsistence needs ($\bar{c}$), P_{t+1} reduces TFP, hence incomes and increases the weight of $\bar{c}$. Consequently, the level of IPR-enforcement is time-varying during the transition to the balanced growth path, disregarded which technology is active. Moreover, it is not guaranteed that ν_{t+1} is positive which contrasts item (ii). As the denominator of (31) is always positive, the sign of ν_{t+1} depends on the sign of the nominator. A negative ν_{t+1} is economically meaningless, such that we obtain $\nu_{t+1} = 0$ as a corner solution for $1-\alpha-\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c} \leq 0$. This immediately implies that expected profits of technology owners ($\nu_{t+1}\pi_{m,j,t+1}$) and the equilibrium interest rate (R_{t+1}) determined by (26) drop to zero. Hence, there is no incentive to engage in R&D activities. The economy is situated in a development trap with constant levels of output for a given level of technological knowledge ($N_{j,0} > 0$).[22] Thus, the emergence of low or even no IPR-enforcement is owed to either a low level of technological knowledge and/or a high level of pollution. The economic reasoning is straightforward. When deciding about the optimal enforcement level, the state optimizes the following trade-off: The current young generation benefits from higher enforcement levels due to an increase in R_{t+1}, see (26), while the next period's young generation is adversely affected by higher deadweight losses which reduce their wage incomes, see (27). Since agents impose due to $\bar{c} > 0$ a higher weight on first-period consumption if their incomes are low, the second effect dominates the first one in the government's objective function, if the state of the technology ($N_{j,t+1}$) and the parameter A are comparatively low or the pollution stock (P_{t+1}) is relatively high. In this case the level of IPR enforcement preferred by the state will be rather low and in an extreme case zero. Hence, a development trap may be originated in technological reasons itself or adverse effects of the technology on the environment. The latter can be circumvented by the implementation of abatement measures (see next subsection) or a redirection of innovations towards clean technologies which has been analyzed by Acemoglu et al. (2012).

An increase in technological knowledge compared to the pollution stock increases incomes and reduces the weight of subsistence consumption reflected by the decline in $\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c}$, such that the level of IPR-enforcement increases. Apparently, if the contribution of additional technological knowledge to available incomes is not offset by the adverse effect of pollution on TFP, the economy evolves along a growth path with increasing incentives to enforce IPRs. This occurs because the production of dirty intermediates is not that harmful to the environment, the adverse effect of pollution on TFP is relatively harmless or the public authority is able to constrain the level of pollution over time due to the implementation of public abatement measures. Finally, if green technologies are productive enough, such that an increase in aggregate savings during the course of economic development induces an increase in $d_{c,t}$, innovations are increasingly directed towards green innovations, see also Proposition 1. Thus, a transition to green technologies would contribute to an increase in incomes but avoid the adverse effect of production on the environment, such that in light of the above discussion, the economy exhibits sooner higher incentives to enforce IPRs. In the discussed cases, $\frac{(N_{d,t+1}^{-\sigma}+N_{c,t+1}^{-\sigma})^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c}$ will approach zero, such that marginal losses in the state's objective function decline while the marginal gain reflected by the increase in interest incomes rises. Hence, the enforcement level of IPRs will increase over time and converge to

$$\lim_{t\to\infty} \nu_{t+1} = \nu_* = -\frac{\beta}{\Psi_D[(1+\rho)\beta+\rho]} > 0 \tag{33}$$

corresponding to the case in which $\bar{c} = 0$, see item (ii) of Proposition 2.

The interaction between environmental conditions and IPR enforcement is thus a transitory phenomenon, as ν_* is independent from P_{t+1}.

We now come back to the more general case $\theta \neq 1$. In the log-linear specification discussed so far, savings were independent from the interest rate which in equilibrium equals expected

[22] Since we abstract from any other accumulable asset, savings are zero such that retirement in the second period should be excluded as well and the population works in both periods of life covering consumption needs from respective wage incomes.

profits of technology owners (26). Thus IPR enforcement assured investment in R&D but variations of ν within the [0, 1]-interval had no direct effect on savings. This is different, if $\theta \neq 1$ since then savings are affected by R_{t+1}. If $\theta < 1$ $(\theta > 1)$, an increase in ν_{t+1} raises via (26) R_{t+1} and induces therefore an increase (decline) in S_t. Nevertheless, it is important to note that this does not contradict the analytical results derived for $\theta = 1$. Comparing (29) and (30) shows that the derived effects translate into the more general case $\theta \neq 1$. The difference is that we need to account for the change in the interest rate.[23] Thus, if the economy evolves along a growth path characterized by increasing enforcement levels of IPRs, the induced increase in R_{t+1} induces a further increase in savings ($\theta < 1$) contributing to an additional increase in productivity growth. In period $t + 1$ this (at least) partially offsets higher deadweight losses in response to stronger IPRs, such that the government is more willing to increase the enforcement level of IPRs for the subsequent period compared to the case where $\theta = 1$. Hence, the analytical results for $\theta = 1$ undervalue (overvalue) the desire to enforce IPRs compared to $\theta < 1$ $(\theta > 1)$since the productivity enhancing effect on next periods wages and interest rates are absent.[24]

Regarding the impact of IPR enforcement on the environment, several observations are in order here. First, the government neglects the environmental consequences of higher IPR enforcement since this is not captured in P_{t+1}. In light of (25), we know that higher savings increase the share allocated to green technologies, $d_{c,t}$, only if the state of the green technology is compared to the polluting technology advanced enough. Moreover, and related to the last point, the technology market clearing condition (21) implies that increasing savings induce a complete transformation of the economy towards the green technology only if $1 + \sigma < 0$. Finally, at least during the transition an increase in savings owed to stronger IPRs or productivity growth in general may well go hand in hand with an increase in the pollution stock with adverse effects on total factor productivities.

4.3 Pollution Abatement

Given the commitment to the protection of technological innovations in the next period, as expressed by ν_{t+1}, the state decides about a tax rate, $\tau_t \in [0, 1)$, on labor incomes of the current young generation, in order to finance pollution abatement measures M_t.[25] For the sake of notational convenience, we assume that tax revenues translate in a one-to-one relationship into abatement measures. Imposing, moreover, a balanced budget on government expenditures we obtain

$$M_t = \tau_t w_t. \tag{34}$$

We begin our analysis again with the analytical tractable case, $\theta = 1$.

Proposition 3 *Given the state's objective function (29), the laws of motion for the pollution stock (6) and technological knowledge (9), the gross interest rate (26) and wages (27) , the*

[23] The empirical literature on the exact value of θ is inconclusive. See for example Yogo (2004), Dacy and Hasanov (2011) and Reis Gomes and Paz (2013) for a discussion and some estimates being smaller than 1. On the other hand macroeconomic models suggest most of the times a value slightly larger than one.

[24] Given the uncertainty around the exact level of θ one shouldn't overstretch this insight.

[25] We could assume equivalently a tax on profits in both sectors or the polluting sector, only. This does however not change our results qualitatively, since profits constitute the return on savings financed from labor incomes in the first period of life.

government's first-order condition with respect to τ_t reads

$$\frac{\partial V_t^G}{\partial \tau_t} = (1+\beta)\left[-\frac{w_t}{(1-\tau_t)w_t - \bar{c}} + \frac{\rho}{w_{t+1} - \bar{c}}\frac{\partial w_{t+1}}{\partial \tau_t}\right] + \frac{\beta}{R_{t+1}}\frac{\partial R_{t+1}}{\partial \tau_t} \leq 0, \quad (35)$$

with

$$\frac{\partial w_{t+1}}{\partial \tau_t} = \frac{\mathcal{A}_t^{-1}}{(1+\tau_t w_t)(2\beta+1)}\left[\left[\frac{\mathcal{A}_t}{(1+\beta)(\tilde{\gamma}^{\frac{1}{1+\sigma}}\gamma_d + \gamma_d)}\right]^{-\sigma} + \left[\frac{\mathcal{A}_t\tilde{\gamma}^{\frac{1}{1+\sigma}}}{(1+\beta)(\tilde{\gamma}^{\frac{1}{1+\sigma}}\gamma_d + \gamma_d)}\right]^{-\sigma}\right]^{-\frac{1}{\sigma}} (AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}\mathcal{B}_t \gtrless 0, \quad (36)$$

and

$$\frac{\partial R_{t+1}}{\partial \tau_t} = \frac{\mathcal{A}_t^{-1}}{(\alpha-1)\Psi_D(2\beta+1)}\left[\beta\gamma_c\bar{\pi}w_t\left[\mathcal{C}_t - \mathcal{D}_t\bar{c}\beta\gamma_c\gamma_d(1+\tau_t w_t)\right]\right] \gtrless 0, \quad (37)$$

where $\bar{\pi} \equiv (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}}(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}})^{-\frac{1+\sigma}{\sigma}}$, $\mathcal{A}_t, \mathcal{C}_t, \mathcal{D}_t > 0$ *and* $\mathcal{B}_t \gtrless 0$.[26]

In (35), $-\frac{w_t}{(1-\tau_t)w_t-\bar{c}}$ represents the marginal utility loss due to income taxation. Clearly, for $\tau_t > 0$ it is necessary that (35) holds with equality, such that the marginal utility loss of the current young generation is compensated by a corresponding increase in interest payments when this generation is old ($\frac{\beta}{R_{t+1}}\frac{\partial R_{t+1}}{\partial \tau_t} > 0$), and or an increase in labor incomes of the next generation discounted with ρ, meaning that $\frac{\rho}{w_{t+1}-\bar{c}}\frac{\partial w_{t+1}}{\partial \tau_t} > 0$. Hence, $\frac{\partial V_t^G}{\partial \tau_t} = 0$ holds only, if $\frac{\partial R_{t+1}}{\partial \tau_t} > 0$ and or $\frac{\partial w_{t+1}}{\partial \tau_t} > 0$.

Let's consider $\frac{\partial w_{t+1}}{\partial \tau_t}$. First note that $\mathcal{A}_t$ reads as

$$\mathcal{A}_t = (1+\beta)(\gamma_d N_{c,t} + \gamma_c N_{d,t}) + \beta[\gamma_c\gamma_d((1-\tau_t)w_t - \bar{c})] > 0, \quad (38)$$

given that disposable incomes are above subsistence needs. Obviously, $sgn\{\frac{\partial w_{t+1}}{\partial \tau_t}\} = sgn\{\mathcal{B}_t\}$, where

$$\mathcal{B}_t = \beta(1+\beta)[\overbrace{\gamma_c\gamma_d(\gamma((1-\tau_t)w_t - \bar{c}) - (1-\alpha)(1+\tau_t w_t))]}^{I} \quad (39)$$

$$+ \underbrace{\gamma(1+\beta(2+\beta))(\gamma_d N_{c,t} + \gamma_c N_{d,t})}_{II} \gtrless 0. \quad (40)$$

Thus, a necessary condition for $\mathcal{B}_t < 0$ is that the first term of the above expression (I) becomes negative, such that

$$w_t\left(1 - \tau_t - \frac{1-\alpha}{\gamma}\tau_t\right) < \bar{c} + \frac{1-\alpha}{\gamma}. \quad (41)$$

The last expression and (27) indicate that $\mathcal{B}_t < 0$ results from a low level of technological knowledge, a high level of subsistence needs ($\bar{c}$) and a high ratio between the labor income share and the elasticity of output with respect to pollution ($(1-\alpha)/\gamma$).[27] If thus the stock of technological knowledge increases, it will become less likely that (41) holds or the potentially

[26] For the sake of visual clarity, we specify $\mathcal{A}_t, \mathcal{B}_t, \mathcal{C}_t$ and $\mathcal{D}_t$ in the subsequent discussion.

[27] If this ratio is high, the labor income share is relatively high while the adverse impact of pollution on output is relatively small, such that a high tax rate is comparatively less required.

negative first term (I) will be overcompensated by the second term (II) which also increases due to technological innovations, such that $\mathcal{B} > 0$ eventually implies that $\frac{\partial w_{t+1}}{\partial \tau_t} > 0$.

A similar economic reasoning applies to the emergence of $\frac{\partial R_{t+1}}{\partial \tau_t} > 0$ which requires that $\mathcal{C}_t > \mathcal{D}_t \bar{c} \beta \gamma_c \gamma_d (1 + \tau_t w_t)$, where

$$\mathcal{C}_t = (A P_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}} \gamma [\beta \gamma_c \gamma_d [(1 - \tau_t) w_t - \bar{c}] + (1 + \beta)(N_{c,t} \gamma_d + N_{d,t} \gamma_c)] > 0 \quad (42)$$

and

$$\mathcal{D}_t = \left[\left[\frac{\mathcal{A}_t \tilde{\gamma}^{\frac{1}{1+\sigma}}}{(1 + \beta)(\tilde{\gamma}^{\frac{1}{1+\sigma}} \gamma_d + \gamma_d)} \right]^{-\sigma} + \left[\frac{\mathcal{A}_t}{(1 + \beta)(\tilde{\gamma}^{\frac{1}{1+\sigma}} \gamma_d + \gamma_d)} \right]^{-\sigma} \right]^{\frac{1}{\sigma}} \quad (43)$$

From the last two expressions it follows that $\mathcal{C}_t$ is increasing in technological knowledge while $\mathcal{D}_t$ is declining in technological knowledge.[28] Thus, the stronger the enforcement of IPRs, the faster $\mathcal{C}_t$ catches up with $\mathcal{D}_t \bar{c} \beta \gamma_c \gamma_d (1 + \tau_t w_t)$.

Coming back to the more general case $\theta \neq 1$, the implementation of tax-financed pollution abatement measures does not differ qualitatively from the special case $\theta = 1$. This contrasts the discussion of IPR enforcement of the previous subsection. The reason for this result is that income taxation and a reduced pollution stock have a direct growth effect through a variation in savings which is also present in the $\theta = 1$ case. The only difference is again that in the log-linear case, savings are not affected by changes in R_{t+1}.

The interesting point is, that abatement measures require sufficiently high incomes generated by innovations that may be increasingly harmful to the environment as long as the dirty technology is active. Again, for a sustained growth path it is necessary that further innovations' value added to available incomes is positive and not diluted by its adverse effect on the environment. If the latter is the case either (41) may hold or the magnitude of $\frac{\partial w_{t+1}}{\partial \tau_t} > 0$ may be reduced in response to a high pollution stock. Similarly, $\mathcal{C}_t$ may not catch up with $\mathcal{D}_t$ or any positive distance between the two may be reduced, such that $\frac{\partial R_{t+1}}{\partial \tau_t}$ is reduced. Thus, the incentives to abate depend on available incomes which depend on the enforcement level of IPRs. Given the just stressed arguments, the incentive to abate is like the incentive to enforce IPRs increasing in the contribution of further innovations to available incomes and declining in the pollution stock. Apparently, the direction of innovation steers also the incentive to abate. If innovations are directed towards green innovations the value added of new technological knowledge is increasing and thus promoting the incentive to abate.

5 Discussion

Closed Economy Assumption In this paper, we explored the interaction between the enforcement level of IPRs and the willingness to pay for tax-financed abatement measures. The analytically derived trade-offs shed light on the observed clash of interests between the developed North and the (developing) South which is characterized by low incentives to enforce IPRs and a low willingness to pay for abatement measures in the latter as compared to the former. It is our strong believe, that the here suggested theory helps to understand the obstacles faced by the South when it comes to international negotiation rounds dealing with the harmonization of IPRs and the mitigation of climate change. Nevertheless, we have to acknowledge in this context some restrictions stemming from our closed economy

[28] Note that $\mathcal{A}_t$ is increasing in technological knowledge, see (38).

assumption. The restrictions result mainly from the abstraction from negotiation rounds (non-cooperative Nash-bargaining) about the level of IPRs and abatement measures. While the core trade-offs of the closed economy will be conserved, the incentives to free-ride on other countries' or regions' effort to enforce IPRs or to abate is absent in our framework. Like in Schäfer and Schneider (2015), we expect that the incentives to free-ride is declining in the market size of a country or region but counteracted by the here introduced hierarchy of needs. The in depth analysis of the source and consequences of the incentives to free-ride deserves certainly more interest and is left for future research.[29]

Big-Push Our theory suggests the emergence of a poverty/pollution trap, if initially the level of technological knowledge is compared to the pollution stock too low or if during the transition the contribution of innovations to available incomes is offset by the productivity dampening effect of pollution. In this case, the economy is unable to disengage itself from this trap by its own efforts. Although, we considered a limited set of policy instruments it is quite unlikely that the state has an incentive to subsidize R&D if there is no incentive to enforce IPRs at the same time. Under this circumstances a big push in the tradition of the development literature is needed. This push could be initiated by a technology transfer from the North to the South, preferably consisting of green technologies. Green technologies have, as has been discussed, the advantage to increase incomes and thus the incentive to enforce IPRs and to abate at higher levels without reducing TFP by increasing levels of pollution. The stability of the poverty trap stems form the hierarchy of needs which imposes high weights on current consumption even in the state's objective function. Obviously, this feature is also owed to the short planning horizon of the government, such that it ignores the benefits of its polices beyond the subsequent period. But it should be noticed that this is a fairly realistic assumption for developing countries and even for most developed countries, if we bear in mind that one period encompasses several decades. Nevertheless, taking the big-push theory at face value (Murphy et al. 1989; Acemoglu 2009), it allows for the coexistence of multiple equilibria that may be reached under different expectations about the profitability of technological alternatives, given the same preferences, technologies and factor endowments. The economic mechanism here is a coordination of agents in a self-fulfilling prophecy manner to an inferior or superior equilibrium. Then, the evolution of the economy is entirely driven by expectations rather than history like it is the case in models of directed technical change. To the best of our knowledge, there are only few models in the literature that discuss the interaction between history and expectations in response to economic policies.[30] An alternative channel to pave the way for sustained economic growth, discussed in the development literature, is the reform of institutions which translates into a higher total factor productivity (A). These reforms include the reduction of red tape or corruption in the administration and would increase the productivity of governmental expenditures and thus private factors of production. This mechanism is probably the only one, apart from the big-push argument, which could be achieved by an economy situated in a poverty trap by its own efforts.[31]

Relation to the DTC Literature A natural point of reference is Acemoglu et al. (2012) who discuss a directed technical change model with an exhaustible natural resource and an environmental pollution externality. There, it is shown that the socially optimal solution can be implemented by a carbon tax and a subsidy to the green R&D sector. The later the

[29] The methodological problem in general is the analytical tractability of the reaction functions of the countries if all countries exhibit active R&D and given that we consider two policy instruments in a directed technical change framework.

[30] See Bretschger and Schaefer (2016) as well as van der Meijden and Smulders (2014) for further details.

[31] See for example Schäfer and Steger (2014).

intervention during the transition occurs, the more expensive the redirection of innovations will be. This results would clearly survive in our framework. Nevertheless, our framework differs along several dimensions from Acemoglu et al. (2012). First, we introduce endogenous IPRs which are due to the trade-off between static deadweight losses and dynamic gains from new inventions not necessarily complete. That alone would apparently just reduce the incentives to innovate. As we introduce in addition a hierarchy of needs, the economy is during the transition to a long-run equilibrium with positive productivity growth characterized by increasing incentives to enforce IPRs and thus increasing incentives to innovate. Thus, if an economy needs to be redirected towards clean innovations during earlier stages of economic development, the subsidies to achieve the same effect are probably higher compared to the reference scenario with complete IPRs. Given the low level of incomes it is also unlikely that the society is willing to pay sufficiently high subsidies. This will delay the transition to clean innovations and shift costs into the future. Finally, the last argument will be aggravated by the third distinguishing feature compared to Acemoglu et al. (2012). Since we consider here the incentives to enforce IPRs and to finance abatement measures of a government that is characterized by a limited planning horizon, we neglect future social gains from these policies, such that also from the political sphere the transition to green technologies will be further delayed into the future.

6 Summary and Conclusions

This paper has examined the interaction between endogenous enforcement of intellectual property rights (IPRs) and tax-financed pollution abatement measures within the frame of a directed technical change model. Households are subject to a hierarchy of needs due to the existence of subsistence consumption. Moreover, the government has a limited planning horizon since it is not able to commit itself to policies for the indefinite future. In addition, the use of polluting intermediates creates in contrast to clean intermediates a negative pollution externality to the total factor productivity.

The existence of a hierarchy of needs implies that the incentive to enforce IPRs is increasing during the transition if the contribution of new innovations to available incomes is not offset by an increase in the pollution stock. If this is not the case, the economy converges to or is already situated in a pollution/development trap. Similar, the willingness to pay for tax-financed abatement measures depends also on the net-value added of innovations. Hence, the incentives to enforce IPRs and to abate are reinforcing. Moreover, both increase if the research is redirected towards clean innovations since then the productivity dampening effect of pollution is circumvented. We argue that this mechanism provides a theoretical foundation for the observed clash of interest between the North and the South when it comes to international negotiation rounds regarding the harmonization of IPR-enforcement and to combat climate change. As moreover our results indicate that a transition to green technologies is supported endogenously, if the green technology is compared to the dirty technology productive enough, a green technology transfer to developing countries would increase the incentives to enforce IPRs and to abate.

Mathematical Appendix

Demand for $x(i)$

Profits of intermediate producers read

$$\pi_{Y_j,t} = p_{j,t}Y_{j,t} - w_t L_{j,t} - \int_0^{\nu_t N_{j,t}} p_{m,j,t}(i)x_{m,j,t}(i)di - \int_0^{(1-\nu_t)N_{j,t}} p_{c,j,t}(i)x_{c,j,t}(i)di \tag{44}$$

$\frac{\partial \pi_{Y_j,t}}{\partial x_{m,j,t}(i)} = 0$ implies

$$x_{m,j,t}(i) = \left(\frac{\alpha A p_{j,t}}{p_{m,x_j,t}(i)}\right)^{\frac{1}{1-\alpha}} L_{j,t}. \tag{45}$$

Machine producers maximize $\pi_{m,j,t}(i) = (p_{m,j,t}(i) - 1)x_{m,j,t}(i)$ with respect to $p_{m,j,t}(i)$ and take (45) as given, such that

$$p_{m,j,t}(i) = \frac{1}{\alpha} \tag{46}$$

and

$$x_{m,j,t}(i) = x_{m,j,t} = \alpha^{\frac{2}{1-\alpha}}(Ap_{j,t})^{\frac{1}{1-\alpha}} L_{j,t}. \tag{47}$$

Symmetrically we obtain from $\frac{\partial \pi_{Y_j,t}}{\partial x_{c,j,t}(i)} = 0$, given that $p_{c,x_j,t}(i) = p_{c,x_j,t} = 1$

$$x_{c,j,t}(i) = x_{c,j,t} = \alpha^{\frac{1}{1-\alpha}}(Ap_{j,t})^{\frac{1}{1-\alpha}} L_{j,t}. \tag{48}$$

Thus,

$$\pi_{m,j,t} = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}}(Ap_{j,t})^{\frac{1}{1-\alpha}} L_{j,t}, \tag{49}$$

$$\pi_{c,j,t} = 0. \tag{50}$$

Labor Market

Output in sector j writes in a symmetric equilibrium as

$$Y_{j,t} = AL_{j,t}^{1-\alpha}[\nu_t N_{j,t}x_{m,j,t}^{\alpha} + (1-\nu_t)N_{j,t}x_{c,j,t}^{\alpha}]. \tag{51}$$

Noting in light of (47) and (48) that $x_{m,j,t} = x_{c,j,t}\alpha^{\frac{1}{1-\alpha}}$, we obtain further

$$Y_{j,t} = p_{j,t}^{\frac{\alpha}{1-\alpha}} A^{\frac{1}{1-\alpha}} L_{j,t}[1 + \nu_t(\alpha^{\frac{\alpha}{1-\alpha}} - 1)]. \tag{52}$$

Maximization of (44) with respect to $L_{j,t}$ yields

$$(1-\alpha)p_{j,t}\frac{Y_{j,t}}{L_{j,t}} = w_{j,t}, \tag{53}$$

such that together with (52) and $w_t = w_{c,t} = w_{d,t}$

$$\frac{p_{c,t}}{p_{d,t}} = \left(\frac{N_{c,t}}{N_{d,t}}\right)^{-(1-\alpha)}. \tag{54}$$

Observing that profit maximizing demand for intermediates in final good production implies

$$\frac{p_{c,t}}{p_{d,t}} = \left(\frac{Y_{c,t}}{Y_{d,t}}\right)^{-\frac{1}{\varepsilon}}. \tag{55}$$

Combining the last expression with (52) and then with (54) yields

$$\left(\frac{p_{c,t}}{p_{d,t}}\right)^{\frac{\alpha}{1-\alpha}} \frac{L_{c,t}}{L_{d,t}} \frac{N_{c,t}}{N_{d,t}} = \left(\frac{p_{c,t}}{p_{d,t}}\right)^{-\varepsilon}, \tag{56}$$

$$\frac{L_{c,t}}{L_{d,t}} = \left(\frac{N_{c,t}}{N_{d,t}}\right)^{-\sigma}, \tag{57}$$

with $\sigma = (1-\alpha)(1-\varepsilon)$.

Noting now that $L_{c,t} + L_{d,t} = 1$ implies finally

$$L_{c,t} = \frac{1}{1+\left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}, \tag{58}$$

$$L_{d,t} = \frac{\left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}{1+\left(\frac{N_{c,t}}{N_{d,t}}\right)^{\sigma}}. \tag{59}$$

$Y_{c,t}$, $Y_{d,t}$, Y_t and w_t

Given that $P_t^{\gamma}(p_{c,t}^{1-\varepsilon} + p_{d,t}^{1-\varepsilon})^{\frac{1}{1-\varepsilon}} = 1$ implies

$$p_{c,t} = P_t^{-\gamma}\left[1+\left(\frac{p_{d,t}}{p_{c,t}}\right)^{1-\varepsilon}\right]^{\frac{1}{\varepsilon-1}}. \tag{60}$$

Combining the last expression with (52) implies

$$Y_{c,t} = P_t^{-\gamma}\left[1+\left(\frac{p_{d,t}}{p_{c,t}}\right)^{1-\varepsilon}\right]^{\frac{\alpha}{(1-\alpha)(\varepsilon-1)}} A^{\frac{1}{1-\alpha}} L_{c,t} N_{c,t}[1+\nu_t(\alpha^{\frac{\alpha}{1-\alpha}}-1)]. \tag{61}$$

The last equation implies together with (54) and (58)

$$Y_{c,t} = (AP_t^{-\alpha\gamma})^{\frac{1}{1-\alpha}}[N_{d,t}^{\sigma} + N_{c,t}^{\sigma}]^{-\frac{\alpha+\sigma}{\sigma}} N_{d,t}^{\alpha+\sigma} N_{c,t}[1+\nu_t(\alpha^{\frac{\alpha}{1-\alpha}}-1)]. \tag{62}$$

Proceeding in a symmetric fashion with $Y_{d,t}$ yields

$$Y_{d,t} = (A^{-\alpha\gamma})^{\frac{1}{1-\alpha}}[N_{d,t}^{\sigma} + N_{c,t}^{\sigma}]^{-\frac{\alpha+\sigma}{\sigma}} N_{c,t}^{\alpha+\sigma} N_{d,t}[1+\nu_t(\alpha^{\frac{\alpha}{1-\alpha}}-1)]. \tag{63}$$

Thus

$$Y_t = (AP_t^{-\gamma})^{\frac{1}{1-\alpha}}[N_{d,t}^{\sigma} + N_{c,t}^{\sigma}]^{-\frac{1}{\sigma}} N_{c,t} N_{d,t}[1+\nu_t(\alpha^{\frac{\alpha}{1-\alpha}}-1)]. \tag{64}$$

Observing that $w_t = (1-\alpha)p_{d,t}\frac{Y_{d,t}}{L_{d,t}}$ and substituting of $p_{d,t}$, $Y_{d,t}$ and exploiting the labor market equilibrium conditions yields

$$w_t = (1-\alpha)(AP_t^{-\gamma})^{\frac{1}{1-\alpha}}[N_{d,t}^{\sigma} + N_{c,t}^{\sigma}]^{-\frac{1}{\sigma}} N_{c,t} N_{d,t}[1+\nu_t(\alpha^{\frac{\alpha}{1-\alpha}}-1)] \tag{65}$$

$$\Rightarrow w_t = (1-\alpha)Y_t. \tag{66}$$

ν_{t+1}

Observing (6), and plugging wages (27) and the gross interest rate (26) into (29), the first-order condition reads as

$$\frac{\partial V_t^G}{\partial \nu_{t+1}} = \frac{(1+\beta)\rho(1-\alpha)(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}(N_{d,t+1}^{\sigma}+N_{c,t+1}^{\sigma})^{-\frac{1}{\sigma}}N_{d,t+1}N_{c,t+1}}{(1-\alpha)(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}(N_{d,t+1}^{\sigma}+N_{c,t+1}^{\sigma})^{-\frac{1}{\sigma}}N_{d,t+1}N_{c,t+1}(1+\Psi_D\nu_{t+1})-\bar{c}} + \frac{\beta}{\nu_{t+1}\Psi_D} = 0. \tag{67}$$

The second term of the above expression represents the marginal change in deadweight losses due to an increase in ν_{t+1} which is negative. For $\nu_{t+1} > 0$, this term has to be outbalanced by the first term. This in turn can only occur is this term is positive which requires that the denominator is positive. Manipulating terms gives finally (31).

$g_{c,*} = g_{d,*} = g_*$

Productivity growth in the clean sector reads as

$$g_{N_{c,t}} = \gamma_c d_{c,t}\frac{S_t}{N_{c,t}}. \tag{68}$$

Noting $d_{c,t}$ and $\frac{N_{c,t}}{N_{d,t}} = \tilde{\gamma}^{\frac{1}{1+\sigma}}$, we obtain

$$g_{N_{c,t}} = \gamma_c\left[\frac{\tilde{\gamma}^{\frac{1}{1+\sigma}}\left(1+\gamma_d\frac{S_t}{N_{d,t}}\right)-\frac{N_{c,t}}{N_{d,t}}}{(\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}})\frac{S_t}{N_{d,t}}}\right]\frac{S_t}{N_{c,t}} \tag{69}$$

$$g_{N_{c,*}} = g_{N_{c,t}} = \frac{\gamma_c\gamma_d\frac{S_t}{N_{d,t}}}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}. \tag{70}$$

Similar

$$g_{N_{d,t}} = \gamma_d(1-d_{c,t})\frac{S_t}{N_{d,t}} \tag{71}$$

implies

$$g_{N_{d,*}} = g_{N_{d,t}} = \frac{\gamma_c\gamma_d\frac{S_t}{N_{d,t}}}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}, \tag{72}$$

such that $g_* = g_{N_{c,*}} = g_{N_{d,*}}$, where

$$\frac{S_t}{N_{d,t}} = \frac{\beta}{1+\beta}\left[(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}(1+\nu_t\Psi_D)-\frac{\bar{c}}{N_{d,t}}\right]. \tag{73}$$

Thus

$$\lim_{t\to\infty}\frac{S_t}{N_{d,t}} = \frac{\beta}{1+\beta}(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}(1+\nu_*\Psi_D) \tag{74}$$

$$\lim_{t\to\infty}\frac{S_t}{N_{d,t}} = \frac{\beta}{1+\beta}(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}\left(1-\frac{\beta}{(1+\rho)\beta+\rho}\right) \tag{75}$$

$$\lim_{t\to\infty}\frac{S_t}{N_{d,t}} = \frac{\beta(1-\alpha)}{1+\beta}\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}\left(\frac{\rho(1+\beta)}{(1+\rho)\beta+\rho}\right). \tag{76}$$

Moreover,

$$N_{c,t+1} = \left[1+\frac{\gamma_c\gamma_d\frac{S_t}{N_{d,t}}}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}\right]N_{c,t} \tag{77}$$

$$N_{d,t+1} = \left[1+\frac{\gamma_c\gamma_d\frac{S_t}{N_{d,t}}}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}\right]N_{d,t} \tag{78}$$

$$\frac{N_{c,t+1}}{N_{d,t+1}} = \frac{N_{c,t}}{N_{d,t}} = \tilde{\gamma}^{\frac{1}{1+\sigma}} \tag{79}$$

Scale Adjusted System

A scale adjusted variable is defined as

$$\bar{x}_t = x_t(1+g_*)^{-t}. \tag{80}$$

Thus

$$\bar{N}_{j,t+1} = \left[1+\frac{\gamma_c\gamma_d\frac{\bar{S}_t}{\bar{N}_{d,t}}}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}\right]\bar{N}_{j,t}(1+g_*)^{-1}, \tag{81}$$

with

$$\frac{\bar{S}_t}{\bar{N}_{d,t}} = \frac{\beta}{1+\beta}\left[(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}(1+\nu_t\Psi_D)-\frac{\bar{c}}{\bar{N}_{d,t}(1+g_*)^{t+1}}\right] \tag{82}$$

and

$$\lim_{t\to\infty}\frac{\bar{S}_t}{\bar{N}_{d,t}} = \frac{\beta}{1+\beta}(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}\left(\frac{\rho(1+\beta)}{(1+\rho)\beta+\rho}\right), \tag{83}$$

such that

$$g_* = \frac{\gamma_c\gamma_d\beta(1-\alpha)\left(AP_t^{-\gamma}\right)^{\frac{1}{1-\alpha}}\left(1+\tilde{\gamma}^{\frac{\sigma}{1+\sigma}}\right)^{-\frac{1}{\sigma}}\left(\frac{\rho}{(1+\rho)\beta+\rho}\right)}{\gamma_c+\gamma_d\tilde{\gamma}^{\frac{1}{1+\sigma}}}. \tag{84}$$

As $\frac{N_{c,t}}{N_{d,t}}$ is determined by $\tilde{\gamma}^{\frac{1}{1+\sigma}}$, the economy jumps to the BGP, if $\bar{c}=0$. Otherwise, for $\bar{c}>0$, initial conditions determine the final steady state in scale adjusted variables.

The evolution of IPR-enforcement proceeds as follows:

$$\nu_{t+1} = \frac{\beta\left[1-\alpha-\frac{\left[\left(\bar{N}_{d,t+1}(1+g_*)^{t+1}\right)^{-\sigma}+\left(\bar{N}_{c,t+1}(1+g_*)^{t+1}\right)^{-\sigma}\right]^{\frac{1}{\sigma}}}{(AP_{t+1}^{-\gamma})^{\frac{1}{1-\alpha}}}\bar{c}\right]}{\Psi_D(\alpha-1)[(1+\rho)\beta+\rho]}. \tag{85}$$

Note: P_{t+1} is constant in the long-run if abatement measures are implemented.

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