84

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ABSTRACT

We are interested in situations in which governments are committed to some pollution abatement constraint which does not match the society's most preferred level of pollution, like in the current climate change policies undergone on behalf of the Kyoto protocol. We develop an overlapping generations model with capital and pollution in which the individuals care about the environmental quality. We show that slightly improving the intertemporal flexibility of the emission quotas by authorizing two-period backward and forward transfers allows to decentralize the whole optimal growth path at competitive equilibrium.

1. Introduction

This article focuses on situations in which governments are committed to some pollution abatement which does not match the society's most preferred level of pollution. Empirical and policy evidence supports such a mismatch, the most salient one being probably the Kyoto protocol negotiated in 1997 under the UN Framework Convention on Climate Change (UNFCCC) set up at Rio in 1992 (UNFCCC, 2005).[1]

We focus on this Convention for two reasons. On the one hand, it is widely acknowledged that the emission quotas assigned on behalf of the Kyoto protocol are probably non-optimal.[2] The UNFCCC itself recognizes that “the exact impact of the Kyoto Protocol on global GHG[3] emissions is difficult to quantify, yet it represents a first step” (UNFCCC, 2005, p. 37). The Convention addresses this point by authorizing adaptation procedures and renegotiations as time goes on. Thus, Article 7.2 of the Convention specifies that “the Conference of the Parties[4] (…) periodically examines the obligations of the Parties and the institutional arrangements under the Convention, in the light of the objective of the Convention, the experience gained in its implementation and the evolution of scientific and technological knowledge”. Admittedly, the emissions quota set up under the Kyoto protocol are non-optimal but have to be considered as a first-step, thus implying forthcoming gradual adjustments and renegotiations.

On the other hand, a *when-flexibility* is allowed under the Kyoto protocol. Article 3.13 states that “if the emissions of a Party included in Annex I[5] in a commitment period are less than its assigned amount under this Article, this difference shall, on request of that Party, be added to the assigned amount for that Party for subsequent commitment periods”. Yet, while setting the concrete application rules of the protocol, the Marrakech Accords restricted banking to 2.5% of a Party's initial assigned amount. Conversely, if a Party fails to meet its emissions target, it must make up the difference, plus a penalty of 30 per cent, in the following commitment period.[6] So, borrowing is

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[1] Other examples may be the EU-IPPC directive according to which sectoral emissions standards are not revised during roughly fifteen years, because of administrative costs, or the US-Acid Rain Program in which allowances of sulfur dioxide emissions permits are set for thirty years.

[2] The Kyoto protocol is a legally binding treaty that serves the ultimate objective of the UNFCCC, as stated in its Article 2: “The ultimate objective of this Convention (…) is to achieve (…) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.” In this respect, the protocol is just one instrument aiming at legally implementing the Convention. The Kyoto protocol runs over the period 2008 - 2012. After 2012, another protocol is to be required.

[3] GHG stands for greenhouse gases.

[4] A Party is defined as a country having signed the Kyoto protocol.

[5] That is to say, roughly, industrialized countries.

[6] It must also develop a so-called *Compliance Action Plan* and its eligibility to sell emissions rights under emissions trading will be suspended.

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forbidden.[7] This shows that the Convention offers some intertemporal flexibility intended to correct the inefficiency of the emission quota, but it also restricts its use.

In this paper we show that authorizing a better (to be defined thereafter) intertemporal flexibility should be a means to circumvent the sub-optimal emission ceilings, regardless the speed at which this ceiling converges towards the optimal pollution level. For that purpose we develop an overlapping generations model (OLG) in which agents, being short-lived, neglect or ill-estimate the long term impacts of their own decisions. Our model is based on the seminal papers by John and Pecchenino (1994), John et al. (1995) or Ono (1996).

In its purpose, however, our article is closer to the recent paper by Jouvet et al. (2005) in which the environmental policy is the instrument for decentralizing the optimal growth. The policy they consider consists in setting a quota on emissions, creating and auctioning the corresponding amount of pollution rights. However, this result crucially depends on the fact that the competent authority is able to choose the quota which maximizes social welfare. In our article we challenge the robustness of this result by recognizing that many environmental policies actually suffer from failures that potentially affect the fixation of the emission quota. The contribution of our article lies in the promotion of a better *when-flexibility* that succeeds in fully circumventing such failures and in decentralizing the optimal growth path at the competitive equilibrium.

The paper proceeds as follows. In Section 2 we present the model, *i.e.* the agents' choices (government, firms and households) and how the *when-flexibility* could be improved under the UNFCCC. Section 3 defines the intertemporal competitive equilibrium of the economy. In Section 4, after having defined the optimal growth path of the economy, we show how it could be decentralized at the equilibrium despite the failure of the emission quotas. The dynamic properties of this economy are analyzed in Section 5 with some numerical illustrations. The last section concludes.

2. The model

We develop an overlapping-generations (OLG) economy *à la* Allais (1947) and Diamond (1965) with environmental policy. We consider that time is divided in periods of two or three decades and that, at the beginning of each period, an emission quota $\bar{S}_t$ is negotiated at the international level. As the UN Framework Convention explicitly considers the possibility to adapt the emission quota (see Article 7.2 quoted in the introduction) we consider that the quota can be inappropriate on the transition but gradually converges towards the optimal emission level, P^*. In our setting this means that $\lim_{t\to+\infty}\bar{S}_t=P^*$. The government implements this quota $\bar{S}_t$ by selling P_t emission permits to the polluting firms. The revenue of these sales is redistributed to the households according to a parameter $\mu_t\in(0,1)$, where μ_t is the share of revenue accruing to the young. The government budget is always balanced.[8] In this section we present the firms' behavior, the households' behavior and how we propose to improve the *when-flexibility*.

2.1. The firms

Let us consider a constant return to scale technology of production with three factors: capital (K), labor (L) and emissions (E). This technology allows to produce a homogeneous good (Y), the numeraire, used both for consumption and investment. We assume a Cobb–Douglas specification:

$$Y_t = K_t^{\alpha_K} L_t^{\alpha_L} E_t^{\alpha_E} = L_t k_t^{\alpha_K} e_t^{\alpha_E}$$

where k_t and e_t represent capital intensity and emissions per unit of labor.

Capital depreciation is complete at each period. Profit maximization gives the usual conditions between the production factors marginal productivity and their price:

$$w_t = \alpha_L k_t^{\alpha_K} e_t^{\alpha_E} \tag{1}$$

$$R_t = \alpha_K k_t^{\alpha_K-1} e_t^{\alpha_E} \tag{2}$$

$$q_t = \alpha_E k_t^{\alpha_K} e_t^{\alpha_E-1} \tag{3}$$

where w_t is the real wage rate, R_t is the interest factor and q_t is the price of the permits.

The use of environment in production generates pollution which affects the quality of the environment. We define the variable Q_t as an index of the environmental quality. This index follows a specific law of motion influenced by the pollution level:[9]

$$Q_{t+1} = (Q_t - E_t)^{1-\Gamma}\,\overline{Q}^{\Gamma} \tag{4}$$

with $0<\Gamma<1$. The stationary level of environmental quality in the absence of human activity is denoted $\bar{Q}>0$. For example it may represent the pre-industrial greenhouse gases concentration in the atmosphere.[10]

2.2. The households

The population is constant and normalized to 1 ($N=1$). Each individual lives for two periods, youth and old age. The young agent is endowed with one unit of labor which he supplies inelastically for a real wage w_t. He also receives his share μ_t of the revenue raised by the sale of the emission permits to the firms: q_tP_t, where q_t is the permit market price. There are two possible uses for his first-period total income, savings s_t and consumption c_t. He then faces the following budget constraint:

$$w_t + \mu_t q_t P_t = c_t + s_t. \tag{5}$$

When old, his revenue comes from capital income $R_{t+1}s_t$, where R_{t+1} is the interest factor, and his share $(1-\mu_{t+1})$ of the sale of the permits in period $t+1$, $q_{t+1}P_{t+1}$. He consumes all his second-period revenue d_{t+1}. This is summarized by the old-age budget constraint:

$$R_{t+1}s_t + (1-\mu_{t+1})q_{t+1}P_{t+1} = d_{t+1}. \tag{6}$$

The individual's preferences are defined on youth and old-age consumption and on the environmental quality when old. They are specified as follows:

$$U_t(c_t, d_{t+1}, Q_{t+1}) = (1-\beta)\log c_t + \rho(\beta \log d_{t+1} + \delta \log Q_{t+1}) \tag{7}$$

where ρ is the discount factor. The parameter β represents the relative weight of old age consumption in the utility function, it is assumed to

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[7] Interestingly, during the pre-negotiation of the Kyoto protocol, at Berlin in 1995, the proposition 128.1 of the Chairman was that “the Parties who have emissions lower than their commitments (…) should be able to carry forward such emission reduction over-achievement to a future period” (see UNFCCC, 1997).

[8] Note that, under the Kyoto protocol, the emission permits are given for free to polluters. In an OLG framework, this boils down to give a windfall profit to the owners of the firms, *i.e.* to the old generations, which corresponds to $\mu_t=0,\forall t$, in our setting.

[9] This formulation is inspired from Mirman's works, of which Levhari and Mirman (1980), Fisher and Mirman (1992, 1996). It boils down to assume that the dynamics of the environmental quality is similar to the ones of a natural renewable resource whose stock is affected by extraction. It also fits the climate change issue where Q_t is the concentration of greenhouse gases in the atmosphere.

[10] According the Intergovernmental Panel on Climate Change, this concentration was 280 ppmv before industrialization and reaches 520 ppmv today.

be strictly positive. The parameter δ, also strictly positive, reflects the consumer's preferences towards environmental quality.

The problem of the representative agent consists in choosing the amount of savings that maximizes his utility with respect to the budget constraints,

$$\max_{s_t} (1-\beta)\log c_t + \rho\beta \log d_{t+1} + \rho\delta \log Q_{t+1}$$
$$s.t. \begin{cases} c_t = w_t + \mu_t q_t P_t - s_t \\ d_{t+1} = R_{t+1} s_t + (1-\mu_{t+1}) q_{t+1} P_{t+1} \end{cases}.$$

The first-order condition reads:

$$\frac{1-\beta}{w_t + \mu_t q_t P_t - s_t} = \frac{\rho\beta R_{t+1}}{R_{t+1} s_t + (1-\mu_{t+1}) q_{t+1} P_{t+1}}. \tag{8}$$

This equation typically describes the trade-off between consumptions over the life-cycle. Rearranging it, we get the saving decision:

$$s_t = \frac{1}{1-\beta(1-\rho)}\left(\beta\rho(w_t + \mu_t q_t P_t) - (1-\beta)\frac{(1-\mu_{t+1}) q_{t+1} P_{t+1}}{R_{t+1}}\right). \tag{9}$$

The youth and old-age consumption levels directly stem from Eq. (9):

$$c_t = \frac{1-\beta}{1-\beta(1-\rho)}\left(w_t + \mu_t q_t P_t + \frac{(1-\mu_{t+1}) q_{t+1} P_{t+1}}{R_{t+1}}\right) \tag{10}$$

$$d_{t+1} = \frac{\beta\rho R_{t+1}}{1-\beta(1-\rho)}\left(w_t + \mu_t q_t P_t + \frac{(1-\mu_{t+1}) q_{t+1} P_{t+1}}{R_{t+1}}\right). \tag{11}$$

At the household's optimum, saving is an increasing function of the first period income and a decreasing function of the revenue in old age. When the agent anticipates a high revenue from the sale of emission permits when old, he has less incentives to save in order to build up a retirement's income. Consumptions are proportional to the present value of the income over the life-cycle.[11]

2.3. Improving the when-flexibility

We propose to improve the *when-flexibility* of the Kyoto protocol by allowing some intertemporal transfers of the emission quota $\bar{S}_t$ following a *Rule-of-thumb* principle. Let us define this principle.

Definition 1. THE RULE-OF-THUMB PRINCIPLE: *a country is allowed to transfer part of its emission quota from one period to another, backward or forward.*

The *Rule-of-thumb* principle widens the Kyoto protocol rules by allowing a country to transfer both forward (*i.e.* from t to $t+1$) and backward (*i.e.* the opposite direction) some of the emission quotas it owns. At odd with the Kyoto protocol, this principle does not restrict forward transfers and authorizes backward transfers without penalty. However, it does not allow full intertemporal flexibility since it restricts transfers to two subsequent periods only. This principle works as follows. Consider the amount of emission quotas issued over periods t and $t+1$. The emissions before period t and those after $t+1$ are assumed given. When the government transfers parts of the emission quota between these two periods, the aggregate amount of emissions is unchanged over t and $t+1$. Yet, the transfers can flow in two directions. Consider first that, at period t, the emissions of the economy fall short the optimal emissions level, according to the *Rule-of-thumb*-principle, government can fill the gap by taking the amount $\Lambda_t > 0$ of emission quota from the next period quota, $\bar{S}_{t+1}$. In the opposite case when the quota $\bar{S}_t$ exceeds the optimal emissions level, the government has the opportunity to transfer the surplus to the next period ($\Lambda_t < 0$). Hence, given the previous transfer Λ_{t-1}, actual emissions at period t write

$$P_t = \bar{S}_t + \Lambda_t - \Lambda_{t-1}, \tag{12}$$

with $\Lambda_t \lessgtr 0\ \forall t$.

Clearly, the aim of the *Rule-of-thumb* principle is to improve the *when-flexibility* under the Kyoto protocol.

3. Equilibrium analysis

In this section we define and characterize the intertemporal competitive equilibrium. Existence and stability are analyzed.

3.1. The intertemporal competitive equilibrium

Definition 2. The competitive equilibrium. *Given* $\{\bar{S}_t, \Lambda_t, \mu_t\}_{t=0}^{+\infty}$, *the equilibrium is defined by the per capita variables* $\{c_t, d_t, s_t\}_{t=0}^{+\infty}$, *the aggregate variables* $\{K_t, L_t, E_t, Q_t\}_{t=0}^{+\infty}$ *and the prices* $\{w_t, R_t, q_t\}_{t=0}^{+\infty}$ *such that:*

households and firms are at their optimum (the first-order condition of the representative agent (8) *and the three conditions for profit maximization* (1, 2, 3) *are satisfied),*
all the markets clear, i.e. $L_t = N = 1$, $k_{t+1} = s_t$ *and* $E_t = P_t$.

As far as the intertemporal equilibrium is concerned, we characterize capital accumulation and determine consumption decisions in equilibrium. For that we substitute in Eqs. (9)–(11) the prices in equilibrium and we use the market clearing conditions. Hence, the dynamic equation characterizing capital accumulation in equilibrium writes:

$$k_{t+1} = \frac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu_t)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu_{t+1})} k_t^{\alpha_K} P_t^{\alpha_E}. \tag{13}$$

In the same way, we obtain the consumption decisions at the first and the second period:

$$c_t = \frac{(1-\beta)(\alpha_L + \alpha_E\mu_t)(\alpha_K + \alpha_E(1-\mu_{t+1}))}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu_{t+1})} k_t^{\alpha_K} P_t^{\alpha_E} \tag{14}$$

$$d_{t+1} = (\alpha_K + \alpha_E(1-\mu_{t+1})) k_{t+1}^{\alpha_K} P_{t+1}^{\alpha_E}. \tag{15}$$

3.2. Equilibrium properties

From Definition 2 and Eqs. (4) and (13), equilibrium dynamics can be summarized by a system of two equations in the two state variables, k_t and Q_t:

$$\begin{cases} k_t = \dfrac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu_{t-1})}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu_t)} k_{t-1}^{\alpha_K} P_{t-1}^{\alpha_E} \\ Q_t = (Q_{t-1} - P_{t-1})^{1-\Gamma} \overline{Q}^{\Gamma} \end{cases} \tag{16}$$

knowing that P_t evolves according to (12):

$$\Lambda_t = P_t - \bar{S}_t + \Lambda_{t-1}.$$

Following the general approach in the OLG literature, we establish the existence a stable steady state for the dynamics given by Eq. (16).

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[11] This income (which corresponds to the term in brackets in (10) and (11)) is determined by the computation of the intertemporal budget constraint of the agent.

3.2.1. Existence of the steady state

In the long run, we have $P_\infty = \bar{S}_\infty = P^*$.[12] this means that equilibrium emissions converge to the optimal level. Then, evaluating Eq. (16) at steady state yields:

$$\begin{cases} k = \dfrac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu)} k^{\alpha_K}(P^*)^{\alpha_E} \\ Q = (Q-P^*)^{1-\Gamma}\overline{Q}^{\Gamma} \end{cases}. \tag{17}$$

According to the first equation, the equilibrium level for capital is uniquely determined and corresponds to:[13]

$$k^e = \left(\frac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu)}(P^*)^{\alpha_E}\right)^{\frac{1}{1-\alpha_K}}. \tag{18}$$

As for the existence of Q^e, the analysis boils down to examining the solutions to the second equation. A sufficient condition for existence is (see Appendix A.1):

$$\overline{Q} \geq \frac{P^*}{\Gamma(1-\Gamma)^{\frac{1-\Gamma}{\Gamma}}} \tag{19}$$

this condition can read as a restriction on the domain of definition of $\bar{Q}$.

Note that the uniqueness of Q^e requires Eq. (19) to hold with the equality. Otherwise, exactly two solutions exist with the following ranking: $Q^{e-} < \tilde{Q} < Q^{e+}$.

3.2.2. Local dynamics

We analyze the conditions ensuring steady states are asymptotically stable. One may note that the evolutions of state variables are independent from each other. Thus, we obtain a sufficient stability condition for each equation in Eq. (16). Linearizing Eq. (16) around a steady state (k^e, Q^e) yields:

$$\begin{cases} dk_t = \alpha_K \dfrac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu)}(P^*)^{\alpha_E}(k^e)^{\alpha_K-1} dk_{t-1} \\ dQ_t = (1-\Gamma)(Q^e-P^*)^{-\Gamma}\overline{Q}^{\Gamma} dQ_{t-1} \end{cases}. \tag{20}$$

It can be checked that only the "high" steady state (k^e, Q^{e+}) is locally stable while the other one is unstable (see Appendix A.2).

To summarize, this analysis provides the following information. Under condition Eq. (19), for a given set of policy instruments $\{\bar{S}_\infty, \mu_\infty\}$, there exists only one asymptotically stable steady state. It means that if the economy starts with an initial condition (k^0, Q^0) "not too far" from the steady state, then there is a unique equilibrium path that will lead the economy to (k^e, Q^{e+}).

4. Optimal growth and equilibrium

We can now study the optimal growth path and analyze the conditions under which it can be decentralized at equilibrium despite the rigidities.

4.1. The optimal growth path

The optimal solution is given by sequences $\{c_t\}_{t=0}^{\infty}$, $\{d_t\}_{t=0}^{\infty}$ and $\{P_t\}_{t=0}^{\infty}$ which maximize the discounted sum of the utilities of all the generations under the resource constraint of the economy, the dynamics of the environmental quality being given. The problem writes as follows:

$$\max_{\{c_t,d_t,P_t\}} \sum_{t=0}^{\infty} \rho^t((1-\beta)\log c_t + \beta\log d_t + \delta\log Q_t)$$
$$s.t. \begin{cases} k_t^{\alpha_K} P_t^{\alpha_E} = c_t + d_t + k_{t+1} \\ Q_{t+1} = (Q_t - P_t)^{1-\Gamma}\overline{Q}^{\Gamma} \end{cases}.$$

We solve this problem with dynamic programming. In this purpose let us define the following value function:

$$V(k_t, Q_t) = B\log k_t + D\log Q_t + G.$$

The Bellman equation associated with this problem writes:

$$V(k_t, Q_t) = \max_{c_t,d_t,P_t}(1-\beta)\log c_t + \beta\log d_t + \delta\log Q_t + \rho V(k_{t+1}, Q_{t+1}).$$

The resolution (see Appendix B.1) leads to the optimal allocation of resources between consumptions and investment, and the pollution level:

$$c_t^* = (1-\beta)(1-\rho\alpha_K)(k_t^*)^{\alpha_K}(P_t^*)^{\alpha_E} \tag{21}$$

$$d_t^* = \beta(1-\rho\alpha_K)(k_t^*)^{\alpha_K}(P_t^*)^{\alpha_E} \tag{22}$$

$$k_{t+1}^* = \rho\alpha_K(k_t^*)^{\alpha_K}(P_t^*)^{\alpha_E} \tag{23}$$

$$P_t^* = \frac{\alpha_E(1-\rho(1-\Gamma))}{\alpha_E + \delta\rho(1-\Gamma)(1-\rho\alpha_K)} Q_t^*. \tag{24}$$

Consumptions and investment are proportional to output. Investment raises with the share of capital in production. The allocation of global consumption between old and young at period t depends on the weight (β) of each consumption in the preferences. The optimal level of emissions is an increasing function of the environmental quality. Let us re-write Eq. (24) as follows to simplify notations: $P_t^* = \nu Q_t^*$ with

$$\nu = \frac{\alpha_E(1-\rho(1-\Gamma))}{\alpha_E + \delta\rho(1-\Gamma)(1-\rho\alpha_K)}. \tag{25}$$

The share of the environment allocated to production is increasing in the share of pollution in production (α_E) but decreasing in both the weight of the environment quality in preferences (δ) and the marginal damage of pollution in the environmental quality ($1-\Gamma$).

Optimal dynamics are described by the system of equations in the two state variables (k_t^*, Q_t^*)

$$\begin{cases} k_{t+1}^* = \rho\alpha_K(k_t^*)^{\alpha_K}(\nu Q_t^*)^{\alpha_E} \\ Q_{t+1}^* = \lambda(Q_t^*)^{1-\Gamma} \end{cases} \tag{26}$$

with

$$\lambda = \left(\frac{\rho(1-\Gamma)(\alpha_E + \delta(1-\rho\alpha_K))}{\alpha_E + \delta\rho(1-\Gamma)(1-\rho\alpha_K)}\right)^{1-\Gamma}\overline{Q}^{\Gamma}.$$

Notice that the dynamics of environmental quality is independent from the dynamics of capital.

Let us consider now stationary paths. A non-trivial steady state (k^*, Q^*) solves the following system of equations:

$$\begin{cases} k^* = \rho\alpha_K(k^*)^{\alpha_K}(\nu Q^*)^{\alpha_E} \\ Q^* = \lambda(Q^*)^{1-\Gamma} \end{cases}.$$

Direct calculations provide the expressions of Q^* and k^*:

$$(k^*, Q^*) = \left(\left(\rho\alpha_K\left(\nu\lambda^{\frac{1}{\Gamma}}\right)^{\alpha_E}\right)^{\frac{1}{1-\alpha_K}}, \lambda^{\frac{1}{\Gamma}}\right). \tag{27}$$

Thus, there exists a unique non-trivial steady state optimum (k^*, Q^*) which is stable (see Appendix B.2).

We are now able to address the key issue of this paper, *i.e.* to see whether the government is able to drive the economy to this optimal path by applying the *Rule-of-thumb* principle.

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[12] Where the subscript ∞ stands for the limit value of corresponding variables.

[13] The superscript "e" holds for the equilibrium solution.

4.2. Decentralizing the optimal growth path

The role of the government is to set up two-period transfers and to redistribute the proceeds of the sale of the emission permits in such a way that the equilibrium path of the economy coincides with the optimal one. This boils down to choosing the values of the instruments (Λ_t, μ_t) in order to have the equilibrium variables k_{t+1}, c_t, d_t, P_t matching their optimal expressions $k^*_{t+1}c^*_t$, d^*_t, P^*_t. The following proposition shows that, even though the trajectory of emission quotas temporarily departs from the optimal emission level, the *Rule-of-thumb* principle is a means to bring the competitive equilibrium to the optimal growth path.

Proposition. Decentralization of the optimal growth path. *For any trajectory of emission quotas converging to the optimal emission level, the whole optimal growth path can be decentralized by applying the Rule-of-thumb principle if* $\alpha_K \in \left[\frac{\beta-\alpha_E}{1+\beta\rho}, \frac{\beta}{1+\beta\rho}\right]$. *The optimal value of the policy instruments* Λ_t *and* μ_t *write*:

$$\Lambda^*_t = P^*_t - \bar{S}_t + \Lambda^*_{t-1} \tag{28}$$

$$\mu^* = \frac{\alpha_K + \alpha_E - \beta(1-\rho\alpha_K)}{\alpha_E} \tag{29}$$

Proof. *see* Appendix C. □

Since the pollution and the classical OLG externalities are internalized, the competitive equilibrium decentralizes the whole socially optimal path of the economy. Through the transfers of emission quotas between periods $\{\Lambda^*_t\}$ the government is able to

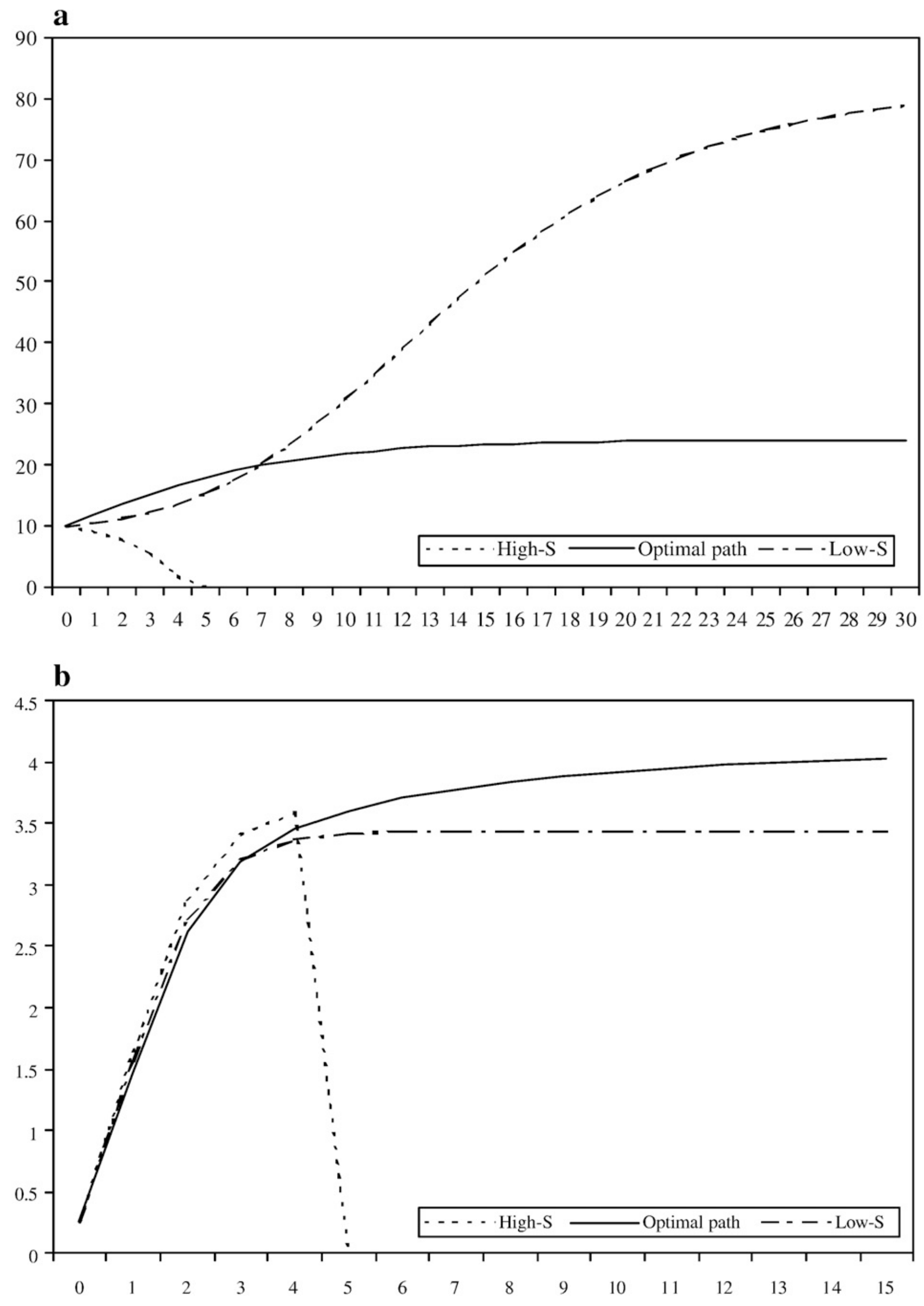

Fig. 1. a: The environmental quality under two non-optimal policies. b: Non-optimal policies: the capital stock.

overcome the non-optimality of the emissions quota $\bar{S}_t$. These transfers ensure that the economy achieves the socially preferred pollution level P_t^*. The sale of the corresponding amount of emissions rights generates a revenue $q_t P_t^*$ accruing to the government. The sharing rule among old and young households $\{\mu^*\}$ works like a lump-sum transfers scheme in the standard overlapping generations model *à la* Diamond (1965). It is well-known that, in the Diamond model without environmental concerns the optimality of the competitive equilibrium can be restored with appropriate lump-sum transfers between generations. The households' incomes profile are affected by these transfers and, consequently, their decisions. Through this channel, the government influences the household's consumption and saving plans. The μ^* sharing rule guarantees that individual decisions coincide with the optimum. The condition on the parameters guarantees that $\mu \in (0,1)$ and is reasonable for reasonable values of the parameters.

The UN Framework Convention opens the door to periodical renegotiations of the emission quotas. As an example, and following the spirit of the Convention, a candidate for a renegotiation rule may depend on the intertemporal transfers realized at time t, Λ_{t-1}, since transfers different from zero indicate that the current emission quota differs from the optimal emissions level. Given the initial emission quota $\bar{S}_0$, all subsequent emission quotas may be renegotiated as $\bar{S}_t = \bar{S}_0 + \phi \Lambda_{t-1}$, with $\phi \in (0,1)$, for all $t > 1$. The adjustment speed depends on the value of ϕ. Knowing that actual emissions are given by $P_t = \bar{S}_t + \Lambda_t - \Lambda_{t-1}$, we combine this expression with the adjustment process $\bar{S}_t = \bar{S}_0 + \phi \Lambda_{t-1}$. This yields time t transfers as follows:

$$\Lambda_t = P_t - \bar{S}_0 + (1 - \phi)\Lambda_{t-1}. \tag{30}$$

Under this adjustment rule, the above proposition holds. In the long run the intertemporal transfer is constant and writes $\Lambda^* = (P^* - \bar{S}_0)/\phi$. The net transfer is nil.

5. Numerical illustrations

This last section makes use of numerical simulations to illustrate how the policy instruments work. Attention is paid to the implementation of the optimal growth path under the *Rule-of-thumb* principle. We first present two scenarios without *when-flexibility*, like under the Kyoto protocol, and then we analyze the functioning of our *Rule-of-thumb* principle.

5.1. Economic and environmental dynamics in the absence of when-flexibility

Let us consider two scenarios which differ according to the level of emission quota $\bar{S}_0$: a high-$\bar{S}_0$ scenario which we will refer to as the *weakly green policy*, and a low-$\bar{S}_0$ scenario which we will refer to as the *strongly green policy*. The former corresponds a latitudinarian environmental policy in which emissions remain too high. This may represent the abatement effort of the Kyoto protocol. The latter scenario represents a much stronger environmental policy in which the emission ceiling is really low. In both scenarios the emission quota is kept constant over time.

What is interesting is to analyze the time profiles for capital stock and environmental quality under the two scenarios, that is, the transition paths and the steady states. They are given in Fig. 1a and b.

The *strongly green policy* leads to a high level of environmental quality in the long run, but this level outreaches the level which maximizes social welfare. Yet, this does not hold in the short term. The economy first experiences a transitory phase of under-accumulation of environmental quality. We know that the optimal emission target moves together with the environmental and the economic dynamics. Actually, even if the fixed quota is too restrictive on the long run it reveals in excess of the optimal target during the first transitional periods. As far as capital accumulation is concerned, the time profile displays symmetrical properties (see Fig. 1b).

During the first periods of the *weakly green scenario*, capital growth is stimulated while the environmental quality decreases. Even though this policy seems profitable to wealth accumulation, its benefits are not long-lasting because it irreversibly damages the natural capital, so that the whole economy collapses after a few periods. This case illustrates what the economy may experience when the environmental policy remains inappropriate for a too-long time span. It sheds light on the interest of improving the *when-flexibility* with our mechanism of intertemporal transfers of pollution quotas.

5.2. The functioning of the Rule-of-thumb principle

Let us introduce our *Rule-of-thumb* principle. We also consider the renegotiation rule given as an example in the previous section, $S_t = \bar{S}_0 +$

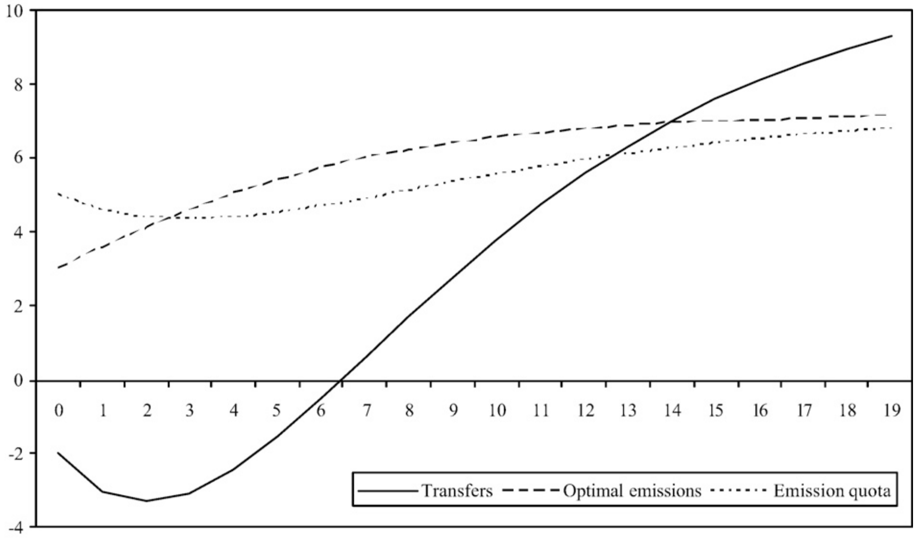

Fig. 2. Time profile of the policy instruments and optimal emissions.

$\phi\Lambda_{t-1}$, with $\phi\in(0,1)$. For the sake of interpretation, given Eq. (30) the optimal pollution level can be rewritten as

$$P_t^* = \underbrace{\left(\bar{S}_0 + \phi\Lambda_{t-1}^*\right)}_{\text{emission quota in } t} + \underbrace{\left(\Lambda_t^* - \Lambda_{t-1}^*\right)}_{\text{net transfer}}. \qquad (31)$$

We further assume that the initial emission quota $\bar{S}_0$ is set at an arbitrarily high level, but below the stationary emissions level, *i.e.* $\bar{S}_0 < P^*$. The dynamics of the two instruments $\{S_t, \Lambda_t\}_{t=0}^{\infty}$ can be analyzed by distinguishing three different phases (see Fig. 2).

During the first three periods t_0, t_1 and t_2, the emission quota remains above the optimal level of emissions ($S_t > P_t^*$). Thus, in order to reach the pollution target, the government transfers quotas from the current period to the next, $\Lambda_t = P_t^* - S_t < 0$. One period later the agency adjusts the quota downward ($S_{t+1} < S_t$), but this revision is only partial ($S_{t+1} > P_{t+1}^*$) and forces the government to transfer more to the next period ($|\Lambda_{t+1}| < |\Lambda_t|$). Therefore, this first phase is characterized by increasing forward transfers ($\Lambda_t < 0$, $|\Lambda_t|$ is increasing) in order to compensate for the incomplete adjustment of the emission quota. Note that the target P_t^* is moving as the economy grows.

From period t_3 onwards, the emission quota falls below optimal emissions ($S_t < P_t^*$, $\forall t \geq t_3$) and the government intervention goes the other way round. The government's net transfer $\Lambda_t - \Lambda_{t-1}$ is now positive and increasing (see Eq. (31)).

Over the periods t_3 to t_6 the government fills the gap $P_t^* - S_t > 0$ by simply reducing its forward transfers ($\Lambda_t < 0$, $|\Lambda_t|$ is decreasing). This is enough to switch the government's net transfer to a positive value. In reaction, the renegotiation process moves the quota upward. After period t_7 the transfers become positive, which means that the transfers now run backward. In the meantime, the renegotiation process keeps on adjusting the quota upward.

In the long run, the renegotiation process guarantees that the emissions quota tends to the optimal pollution level. So, the transfers Λ_t converge to a stationary positive level Λ^* and the government's net transfer is nil.

6. Conclusion

It is widely acknowledged that the Kyoto protocol sets non-optimal emission ceilings to cope with climate change. Despite the allegeable argument of a first step for political acceptability reasons, the question remains on how to implement an optimal emission path for national greenhouse gases. Is it possible to reconcile the negotiation process on emission quotas, which is of a political nature, with an optimal transition path? In a dynamic general equilibrium setting we show that it may be possible by allowing a better intertemporal flexibility of the emission quotas assigned to the countries. Allowing countries to transfer part of their emission quota backward and forward, only over two periods and not in an explosive path, would allow the UN Framework Convention on Climate Change to match the socially optimal path, that is, to prevent dangerous anthropogenic interference with the climate system. This result should be kept in mind when renegotiating a post-Kyoto protocol. In this context, to gauge the sign and the magnitude of the transfers of quotas, a natural extension of our model would consist in modeling shorter periods to fit the Kyoto-commitment time periods, for example in a computable general equilibrium model.

We illustrate the dynamic properties of the transfers mechanism with numerical simulations. Depending on the level of the emission quota the transfers may go forward or backward on the transition path, and they may switch from one regime to the other. In the long run, the government net transfer is equal to zero since the direction and the magnitude of the transfers are replicated identically over time. We also analyze two non-optimal policies labeled respectively as *weakly* and *strongly green*. We show that these labels may be misleading. Indeed, because the optimal emissions level changes over time the so-called *strongly green policy* may actually appear too latitudinarian on the transition path and the *weakly green* one too restrictive. We study the under/over-accumulation of environmental quality and capital per head which occur along non-optimal paths. Especially, in the presence of an overly-generous quota, environmental quality may irreversibly deteriorate within a few periods. This highlights the dynamical and general equilibrium dimensions of environmental management and the need for adequate policy instruments.

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Appendix A. Equilibrium properties

A.1. Existence

The analysis of the existence of Q^e boils down to the examination of the solutions to the equation: $f(Q)=0$ with

$$f(Q) = Q - (Q - P^*)^{1-\Gamma}\overline{Q}^{\Gamma},$$

let us summarize the properties of $f(Q)$. This function is defined for any $Q \geq P^*$ with $f(P^*) = P^* > 0$ and $\lim_{Q\to+\infty} f(Q) = +\infty$ ($f(.)$ is a polynomial in Q with the highest power equals to 1). The derivative is $f'(Q) = 1-(1-\Gamma)(Q-P^*)^{-\Gamma}\overline{Q}^{\Gamma}$ and we easily check that: $f'(Q) \geq 0\ (<0) \leftrightarrow Q \geq \tilde{Q}\ (Q < \tilde{Q})$. Finally, $f(.)$ is convex since $f''(Q) = \Gamma(1-\Gamma)(Q-P^*)^{-\Gamma-1}\overline{Q}^{\Gamma} \geq 0$. This function reaches its minimum at $\tilde{Q}$ and the corresponding level achieved is:

$$f\left(\tilde{Q}\right) = P^* - \Gamma(1-\Gamma)^{\frac{1-\Gamma}{\Gamma}}\overline{Q}.$$

A sufficient condition for the existence of Q^e is $f(\tilde{Q}) \leq 0$ since it guarantees that there exists an intersection between $f(.)$ and the horizontal axis. This condition can read as a restriction on the domain of definition of the scale parameter $\bar{Q}$:

$$\overline{Q} \geq \frac{P^*}{\Gamma(1-\Gamma)^{\frac{1-\Gamma}{\Gamma}}},$$

and note that the unicity of Q^e requires that Eq.(19) holds with the equality. Otherwise, exactly two solutions exist with the following ranking: $Q^{e-} < \tilde{Q} < Q^{e+}$.

A.2. Stability

Stability of the dynamics given by Eq. (20) first requires: $\frac{dk_t}{dk_{t-1}} < 1$. According to Eq. (18), this condition is necessarily satisfied since

$$\frac{dk_t}{dk_{t-1}} = \alpha_K \frac{\beta\rho\alpha_K(\alpha_L + \alpha_E\mu)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu)}(P^*)^{\alpha_E}(k^e)^{\alpha_K} = \alpha_K < 1.$$

The second stability condition, $\frac{dQ_t}{dQ_{t-1}} < 1$, writes:

$$(1-\Gamma)(Q^e - P^*)^{-\Gamma}\overline{Q}^{\Gamma} < 1 \text{ or } f'(Q^e) > 0.$$

Now, it is clear, from the properties of $f(.)$, that only the “high” steady state (k^e, Q^{e+}) is locally stable since $f'(Q^{e+}) > 0$. The other one is unstable.

Appendix B. Optimum analysis

B.1. Derivation of optimal solutions

Using the definitions of k_{t+1} and Q_{t+1} in the constraints, the problem is equivalent to the following:

$$\begin{aligned}\max_{c_t,d_t,P_t} & (1-\beta)\log c_t + \beta \log d_t + \delta \log Q_t \\ & +\rho\left\{B\log\left(k_t^{\alpha_K}P_t^{\alpha_E}-c_t-d_t\right)+D\log\left(\left(Q_t-P_t\right)^{1-\Gamma}\overline{Q}^{\Gamma}\right)+G\right\}.\end{aligned}$$

The first-order conditions write:

$$\begin{aligned}\frac{1-\beta}{c_t} &= \frac{\rho B}{k_t^{\alpha_K}P_t^{\alpha_E}-c_t-d_t} \\ \frac{\beta}{d_t} &= \frac{\rho B}{k_t^{\alpha_K}P_t^{\alpha_E}-c_t-d_t} \\ \frac{\rho B\alpha_E k_t^{\alpha_K}P_t^{\alpha_E-1}}{k_t^{\alpha_K}P_t^{\alpha_E}-c_t-d_t} &= \frac{(1-\Gamma)\rho D}{Q_t-P_t}.\end{aligned}$$

The first two conditions give us the relation between c_t and d_t:

$$d_t = \frac{\beta}{1-\beta}c_t. \tag{32}$$

By substituting Eq. (32) in the first equation we get the consumption decision c_t. Hence d_t can be deduced from Eq. (32):

$$c_t = \frac{(1-\beta)k_t^{\alpha_K}P_t^{\alpha_E}}{1+\rho B} \tag{33}$$

$$d_t = \frac{\beta k_t^{\alpha_K}P_t^{\alpha_E}}{1+\rho B}. \tag{34}$$

Substituting c_t and d_t in the third condition with the last two expressions gives the emissions level:

$$P_t = \frac{\alpha_E(1+\rho B)}{(1+\rho B)\alpha_E + (1-\Gamma)\rho D}Q_t. \tag{35}$$

Let us replace these intermediate solutions (33)–(35) in the Bellmann equation so as to identify the coefficients B and D:

$$\begin{aligned}B &= \frac{\alpha_K}{1-\rho\alpha_K} \\ D &= \frac{\alpha_E + \delta(1-\rho\alpha_K)}{(1-\rho\alpha_K)(1-\rho(1-\Gamma))}\end{aligned}.$$

Hence, we characterize the optimal allocation of the resources between consumption and investment, and the emissions level, by substituting the value of these coefficients in Eqs. (33)–(35).

B.2. Optimal dynamics

Linearizing Eq. (26) around the steady state (k^*, Q^*) gives:

$$\begin{cases} dk_{t+1}^* = \rho\alpha_K\left(\alpha_K(k^*)^{\alpha_K-1}(\nu Q^*)^{\alpha_E}dk_t^* + \alpha_E\nu(k^*)^{\alpha_K-1}(\nu Q^*)^{\alpha_E-1}dQ_t^*\right) \\ dQ_{t+1}^* = (1-\Gamma)\lambda(Q^*)^{-\Gamma}dQ_t^* \end{cases}.$$

By making use of the optimal values of k^* and Q^*, basic calculations provide the Jacobian matrix:

$$J = \begin{pmatrix} \alpha_K & \phi \\ 0 & 1-\Gamma \end{pmatrix}$$

with,

$$\phi = \alpha_E\nu\left(\nu\lambda^{\frac{1}{\Gamma}}\right)^{\frac{\alpha_E}{1-\alpha_K}}(\rho\alpha_K)^{\frac{\alpha_K}{1-\alpha_K}}.$$

Stability requires the two roots of the characteristic polynomial to be located into the unit circle, all other configuration being unstable. We know that the trace corresponds to the sum of the (real parts) eigenvalues of J and, the determinant is the product, in modulus, of the eigenvalues. Here, the two eigenvalues are $R_1=\alpha_K<1$ and $R_2=1-\Gamma<1$. Thus, the optimal solution is locally stable.

Appendix C. Decentralization

The period t equilibrium emissions are given by:

$$P_t = \overline{S} - \Lambda_{t-1} + \Lambda_t$$

i.e. the volume of the quota ($\bar{S}$) less the amount transferred to period $t-1$ ($\Lambda_{t\ -1}$) and plus the amount transferred from period $t+1$ to period t (Λ_t). The government determines its policy in order to realize the equality between equilibrium and optimal emissions, $P_t^*=\bar{S}_t+\Lambda_t-\Lambda_{t\ -1}$. Given the initial transfer Λ_0 and the optimal emissions path P_t^* the optimal policy of the government is determined by the choice of the sequence of transfers Λ_t^* such that $P_t^*=P_t$. The pollution target is thus achieved by choosing the sequence Λ_t^* which satisfies, at any time t: $\Lambda_t^*=P_t^*-\bar{S}_t+\Lambda_{t\ -1}^*$.

By studying the government optimal distribution of the auction proceeds we decentralize the optimal consumptions and capital accumulation. First, using Eqs. (13) and (23), the matching between equilibrium and optimal capital accumulation, $k_{t+1}=k_{t+1}^*$, implies:

$$\rho\alpha_K k_t^{\alpha_K}P_t^{\alpha_E} = \frac{\beta\rho\alpha_K(\alpha_L+\alpha_E\mu_t)}{(1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu_{t+1})}k_t^{\alpha_K}P_t^{\alpha_E}.$$

This yields the following relation between μ_t and μ_{t+1}:

$$\beta(\alpha_L+\alpha_E\mu_t) = (1-\beta(1-\rho))\alpha_K + (1-\beta)\alpha_E(1-\mu_{t+1}). \tag{36}$$

To identify consumption we use Eq. (36) in the expression of equilibrium consumption Eq. (14), which yields:

$$c_t = \frac{1-\beta}{\beta}k_t^{\alpha_K}P_t^{\alpha_E}\left(\alpha_K + \alpha_E(1-\mu_{t+1})\right) \tag{37}$$

and we equate the latter equation with Eq. (21):

$$(1-\beta)(1-\rho\alpha_K)k_t^{\alpha_K}P_t^{\alpha_E} = \frac{1-\beta}{\beta}\left(\alpha_K + \alpha_E(1-\mu_{t+1})\right)k_t^{\alpha_K}P_t^{\alpha_E}.$$

The value of μ_{t+1} which solves this equation is than plugged into Eq. (36) in order to obtain the optimal value of the share of the proceeds accruing to the young at any time t:

$$\mu_t^* = \mu_{t+1}^* = \frac{\alpha_K+\alpha_E-\beta(1-\rho\alpha_K)}{\alpha_E}. \tag{38}$$

If the government follows, each period, this rule Eq. (38) of distribution among young and old households, it simultaneously decentralizes consumptions and capital accumulation.

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