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A rationale for the Right-to-Development climate policy stance?☆

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ABSTRACT

We present a formal model that analyzes the trade-offs between environmental policy and economic growth in a developing economy. The adoption of restrictive environmental policies limits the use of abundant fossil energy resources, which may slow down economic development and thus violate the *Right-to-Development*. If faster economic growth allows a country to grow out of pollution sooner, less stringent policies are good for growth and even for the environment, having adopted a long-term horizon. Accounting for a ceiling on cumulative emissions can reinforce the argument by providing an additional rationale to phase out pollution. One assumption is crucial for the argument to hold: polluting fossil energy is an essential input over the early phase of economic development, but not in the later phases. Such a discontinuity could result from structural change. We provide empirical evidence for the plausibility of a discontinuity in the elasticity of carbon dioxide emissions with respect to aggregate output, using cross country data, even if it does not appear to be as strong as assumed in the model economy.

1. Introduction

The Right-to-Development (RtD) recognizes the aspiration of "every human person and all peoples [...] to participate in, contribute to, and enjoy economic, social, cultural and political development", and requires states to create the conditions favorable to such an outcome.[1] In international climate negotiations, the RtD has been put forward as a limiting factor to climate policy action. As stated in the preamble to the Paris Agreement "when taking action to address climate change, [Parties should] respect, promote

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[1] The RtD is embedded in the 1986 UN Declaration, which was brought about by the Human Rights Commission in response to calls for a new international economic order following decolonization (Teshome, 2022). Although adopted by an extraordinarily wide majority, its formulation is quite vague and constitutes no more than a soft international law.

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and consider their respective obligations on [...] the right to development [...]''.[2] Underpinning developing countries' priorities, this statement expresses their concern about the potential impact of climate action on their prospects of sustained development. This paper presents a rationale for such a concern. It represents economic development as a process of structural change, where energy consumption is both a key driver and potentially harmful. It provides a framework to analyze environmental policy related to energy consumption, and formalizes a trade-off in implementing a restrictive policy. The adoption of restrictive environmental policies limits the use of abundant fossil energy resources, which may slow down economic development and thus violate the RtD. If faster economic growth allows a country to grow out of pollution sooner, less stringent policies are good for growth and even for the environment, by adopting a long-term horizon.

Since it reflects the dialectics between the South and the North in climate policy negotiations, the reference to the RtD could be interpreted in terms of the bargaining process for sharing the burden of climate change mitigation and adaptation. Indeed, a large body of literature is concerned with issues such as fairness, historical responsibilities and political acceptability (Lange et al., 2010; Underdal and Wei, 2015; Rempel and Gupta, 2022). Concerned with international climate negotiations, Bretschger and Vinogradova (2015) is the first paper in economics to provide a theoretical foundation to the RtD argument. The focus is on foreign compensation to developing countries to convince them to join a stringent international climate policy agreement. The authors show that voluntary participation is more likely the greater the number of possible combinations between environmental targets and related financial transfers from abroad. In one of these schemes, targeted at the least developed countries, the constrained path of emissions is allowed to increase over an initial period of time.

In this paper we instead abstract from multilateral bargaining and focus on an argument that could apply to optimal regulation of the growth-pollution nexus within a closed economy. In doing so, we are able to represent the explicit concern of possible harmful consequences of a strict domestic climate policy on the process of economic development.

Scholars have argued that growth in developing countries could be hampered by climate change mitigation. One reason could be that the increased use of more expensive low-carbon energy sources could delay structural change and the development of physical infrastructure (e.g. Jakob and Steckel, 2014). Others have underscored the detrimental consequences on development from limiting exports of fossil resources in some resource rich countries (Armstrong, 2020). These concerns underlie the debate on the definition of *capacity* to act (e.g. Baer, 2013). They are also in the spirit of the environmental Kuznets curve (EKC). One of the arguments for the EKC provided by growth models, such as Stokey (1998) is that in early development stages, an economy finds it worthwhile to use the most productive, but also the dirtiest, technology to create wealth. Then, once the economy becomes rich enough and damage from pollution becomes relatively valuable, it starts using greener technologies, which are typically costly to implement, and pollution eventually falls.

However, there are reasons to be concerned about delays in the implementation of an effective and stringent climate policy, as this could result in welfare losses due to excessive damage or asset depreciation. The literature on tipping points shows that irreversible consequences of climate change may invalidate the optimality of the EKC (van der Ploeg and de Zeeuw, 2018; van der Ploeg, 2016). Other arguments favor an early environmental policy. First, expected – rather than immediately implemented – environmental policies may foster fossil fuel exploitation (as oil producers have an incentive to exploit their resources before the implementation of the policy) and therefore emissions, as argued by Hans-Werner Sinn, who first presented this ''green paradox'' (Sinn, 2008). Second, since green investment takes time to implement, it may call for early action as pointed out by Vogt-Schilb et al. (2018) and Stern and Stiglitz (2017).

This would not be an issue if countries could successfully develop their economies without increasing consumption of carbon intensive energy resources, thereby not replicating the historical experience of developed countries. However, such a favorable case, referred to as ''leap-frogging in energy intensity'', does not seem to be empirically grounded. Indeed, in a sample of 76 countries from 1960–2006, van Benthem (2015) finds that the energy intensity of less developed countries today is equivalent to that of richer countries when they were at comparably low income levels. It seems that changes in consumption patterns and trade specialization counter-balanced technological improvements in energy efficiency. Overall, the empirical evidence points to the critical role of energy consumption in the early phases of economic development, and the significant effect of structural change.[3]

The purpose of this paper is to clarify the mechanisms and the assumptions underpinning the RtD policy stance. Recall that this policy stance rebuts environmental regulation in developing economies to the extent that it may be considered excessively strict, in the sense that it would harm prospects for improving living standards. Our analysis shows that this argument makes sense if economic development on its own would bring about an environmentally friendly technological breakthrough. We relate such a situation to the process of structural change, by which the share of the service sector in employment, expenditure and value added increases, while that of agriculture falls, and it evolves in a bell shape for manufacturing.[4] We show that under these circumstances it might be socially preferable to temporarily accept environmental damage caused by the use of dirty energy, to the extent that

[2] The developing countries specified their concerns in terms of vulnerability, capacity and responsibilities regarding international climate law, and asked for assistance. The Group of 77 (the leading group of 147 developing countries at the UN) in paragraph 102 of its November 2021 Ministerial Declaration writes that its engagement in the Paris Agreement shall be in line with the principles of ''common but differentiated responsibilities and respective capabilities, in the light of different national circumstances, and the right to development, in the context of sustainable development and efforts to eradicate poverty''. In the same vein, speaking on behalf of the BASIC group at the 2021 CoP26 of the UNFCCC, the Indian Ministry of the environment stated that ''Developing countries must be accorded time, policy space and support to transition toward a low emissions future [in recognition of] differing historical responsibilities and the severe developmental challenges faced by developing countries''.

[3] See also Jakob et al. (2012), Bretschger (2015), Lechthaler (2017), Deichmann et al. (2019) and Csereklyei et al. (2016).

[4] We equate dirty energy with fossil fuels, which are mostly used for heating, transportation and industry. The two former activities are included in the service sector, which may help explain the lack of empirical evidence for the effect of structural change on energy-related greenhouse gas emissions.

this allows the economy to develop and modernize, in order to permanently shift to a regime where the use of dirty energy can be avoided. In this situation a shortsighted concern for current environmental damage arising from dirty energy use would lead the government to implement a restrictive environmental policy and halt economic development, with a permanent loss in consumption and environmental quality.

The argument we present relies on the distinction between two forms of energy, dirty and clean (e.g. renewable energy) and underscores their asymmetric role in development phases. Hence we assume that energy availability is not a constraining factor in the development of a modern economy based on the service sector, which can indifferently rely on clean or dirty energy. In the case of industrialization we instead suppose that dirty energy plays a crucial role, and that it could become a constraining factor for the development of the manufacturing sector, were it to be made expensive by environmental regulation. Hence, our approach allows us to clarify the role of the assumption in underpinning the policy argument.[5] It also allows us to determine efficient timing in implementing a restrictive environmental policy, artificially rarefying dirty energy.

We consider two types of pollution problems. On the one hand, we introduce damage resulting from the current flow of polluting emissions that reduces households' utility. On the other hand we consider the case where the current use of dirty energy causes lagged catastrophic damage. We formalize this second possibility as damage due to the accumulation of pollution beyond a threshold. We show that the ceiling on pollution actually reinforces the RtD argument. If the social objective is to avoid reaching the threshold, it may be desirable to accelerate the transition toward the clean economy, i.e. anticipating structural change, since the latter is relatively more valuable. However, this implies suffering greater damage from current polluting emissions as well as lowering the consumption level over the transition.

Our methodological approach is similar to Bretschger and Vinogradova (2015) as we obtain solutions in explicit form and compare across policies. Our analysis is carried out in steps. It relies on the assumed presence of two thresholds that are successively introduced. First we consider the structural shift in the aggregate production function, concerning the role of dirty energy as an input. The level of development that triggers structural change is exogenous, but timing is endogenous.[6] Another step is then added for the occurrence of a catastrophic event from excessive accumulation of pollution due to dirty energy use. From a technical point of view, our approach relies on the work of Chakravorty et al. (2006, 2008) and Boucekkine et al. (2013).

Finally, we provide some empirical evidence for the plausibility of our main assumption, namely the existence of a threshold for a structural break in the fossil energy intensity of aggregate output, as described in the theoretical model. Using panel threshold regressions, we show that there is a discontinuity in the elasticity of aggregate output with respect to carbon dioxide emissions (i.e. a proxy for fossil energy use), though less pronounced than that assumed in the theoretical model.

The structure of the paper is as follows. First we present the theoretical model with structural change. Section 2 presents and justifies the model, while its resolution and numerical illustrations of the comparative dynamics across policies are in Section 3. A pollution ceiling is added in Section 4. Section 5 empirically questions the relevance of the main assumption of the theoretical model. Section 6 concludes.

2. A model with structural change

Consider a single representative firm, producing a homogeneous output, y. It potentially employs two inputs: productive capital, k, a stock variable, and dirty (fossil) energy, f, a flow variable. Subject to sufficient energy inputs, the technology is characterized by constant returns to scale with respect to capital.

We assume that the nature of the production process changes with economic development, by becoming less energy intensive. This represents the shift from an economy based on the development of the manufacturing sector to one where services become dominant, characteristic of structural change.

Formally, we introduce a discontinuity in the aggregate production function, concerning the role of energy inputs in production. We assume that there exists a threshold level of aggregate output $\hat{y}$, such that energy is a complementary input to capital inputs for any $y \leq \hat{y}$, but it is an unnecessary input otherwise.

We posit $\exists\ \hat{y} > 0$, thus $\hat{k} \equiv \hat{y}/A,\ A, b > 0$, such that:

$$y_t = \begin{cases} \min\left\{Ak_t, bf_t\right\} & \forall k_t \leq \hat{k} \quad \text{phase 1: industrialization} \\ Ak_t & \forall k_t > \hat{k} \quad \text{phase 2: service economy} \end{cases} \tag{2.1}$$

Capital depreciates at a constant exogenous rate, δ. Forgone consumption, $y - c$, is entirely invested. The law of motion of capital is therefore:

$$\dot{k}_t = y_t - \delta k_t - c_t$$

which can be rewritten, taking into account (2.1) and efficient energy-capital use, as:

$$\dot{k}_t = (A - \delta)\, k_t - c_t \tag{2.2}$$

We assume that $A - \delta > 0$. The initial stock of capital k_0 is given.

[5] The changing role of dirty energy over the development stages can be related to the cost of the energy transition. We consider that the latter falls with structural change (e.g. due to the expansion of electrification). Alternatively, one might consider it as the result of income-driven technological change improving the elasticity of substitution between energy sources (see Jo and Miftakhova, 2024).

[6] Refer to Bretschger et al. (2023) for a model with a technological shift occurring for an endogenous level of capital accumulation.

Dirty energy use implies polluting emissions. Pollution generates local damage, as in the case of PM2.5 concentration in the atmosphere, and is a potential concern for public policy. Each unit of dirty energy consumed generates ζ units of emissions: $e_t = \zeta f_t$.

The Leontief production function in the first line of (2.1), relevant during industrialization, introduces a dichotomy on the constraining factor for economic development. We assume that, absent any environmental concern, capital accumulation is the main driving force of economic development, as dirty energy supply is abundant. To simplify we assume that dirty energy is available at no cost. However, this is no longer the case, and the constraining factor becomes the inelastic supply of dirty energy, if the environmental regulation is stringent enough. For instance, this case would eventually apply if a sufficiently limited amount of emission allowances is auctioned to comply with a ceiling on cumulative emissions, or if an effective cap on the flow of emissions is implemented below the threshold $(\zeta A/b)\hat{k}$.[7]

We consider a representative household, infinitely lived, and of constant size, whose current utility increases with consumption (up to a satiation point) and decreases with the flow of polluting emissions. We analyze the case of a specific representation of current utility:

$$\tilde{u}\left(c_t, e_t\right) = \frac{\gamma}{2} c_t \left(2\bar{c} - c_t\right) - \tilde{\theta} e_t \tag{2.3}$$

We can use the efficient energy-capital use over phase 1 to restate current utility in the following form:

$$u\left(c_t, k_t\right) = \begin{cases} \frac{\gamma}{2} c_t \left(2\bar{c} - c_t\right) - \theta k_t & \forall k_t \leq \hat{k} \quad \text{phase 1} \\ \frac{\gamma}{2} c_t \left(2\bar{c} - c_t\right) & \forall k_t > \hat{k} \quad \text{phase 2} \end{cases} \tag{2.4}$$

where $\theta \equiv \tilde{\theta}\zeta A/b$.

Notice that this utility function is characterized by linear damage from polluting emissions resulting from the use of the capital stock over the industrialization phase, and by a linearly decreasing marginal utility of consumption:

$$u'_c \equiv \frac{\partial u}{\partial c} = \gamma(\bar{c} - c_t)$$

This implies that consumption reaches a satiation point at $c_t = \bar{c}$, and therefore sustained growth is neither an equilibrium outcome, nor an optimal one. We study economic development as a process of transitional dynamics, reminiscent of economic catch-up, and obtain explicit form expressions of endogenous variables because of the linear technology in (2.1) and quadratic utility in (2.3).[8] Besides this advantage, our definition of social welfare in (2.3) puts more emphasis on pollution damage than on benefits from consumption. The former constitutes an unconditional concern, while the latter only a transitory one. Hence any pro-growth outcome favoring consumption over environmental quality is ascribable to the technology.

We study the regulator's problem:

$$(\mathcal{P}): \qquad \max \int_0^\infty e^{-\rho t} u\left(c_t, k_t\right) dt$$
$$\text{s.t. (2.1) with } f_t = \frac{A}{b} k_t, \text{ (2.2), (2.4)}$$

In choosing consumption the regulator determines capital accumulation, thus dirty energy use, output and polluting emissions.

3. The right to development argument

Since our interest lies in developing economies, we restrict the analysis to the case of an industrializing economy, that is one endowed with a capital stock such that the technology is initially intensive in dirty energy, i.e. $k_0 < \hat{k}$. In such a situation the regulator, facing problem $(\mathcal{P})$, determines the optimal regulation taking into account two features of the problem: damage from polluting emissions during industrialization, and the discontinuity in technology related to the structural break.

To conduct our analysis we adopt a progressive approach, starting with two special cases that are of interest in understanding the role of the technological structural break and the mechanisms at work. First, we consider the case of *myopic regulation*, i.e. where the regulator takes into account the damage from polluting emissions when determining the investment policy, but does not foresee the potential structural break. Second, we consider the case of *brown regulation*, that is one where the regulator determines the investment policy abstracting from any damage from polluting emissions. In this case the structural break is irrelevant. Finally, we consider the case of *optimal regulation*, that is one where the regulator is concerned by damage from polluting emissions, and foresighted in understanding the impact of development of the role of polluting inputs through structural change. This is problem $(\mathcal{P})$, which is solved backwards, starting with the case of a service economy (tantamount to that of brown regulation, but for an initial capital endowment above the threshold $\hat{k}$), then studying the full program that includes the solution of the service economy program and in its first phase, the case of an industrialized economy concerned with damage from polluting emissions. This sequential approach allows us to compare the trajectories under optimal regulation with those implied in each case of imperfect regulation. These comparisons are instructive and conducive to the definition of our original rationale for the RtD.

[7] In the Introduction we have motivated our assumption concerning the asymmetric role of dirty and clean energy in the development phases. Arguably, our implicit assumption of free clean energy inputs is extreme. Yet, it does not seem crucial, since we may simply define aggregate product y as output net of the cost of energy inputs. The relevant point is that clean energy is sufficiently abundant to focus on capital as the determining factor of aggregate output.

[8] The same approach is used in Boucekkine et al. (2013).

3.1. Myopic regulation

In this setting, the regulator does not take into account the possibility of a structural break in the aggregate technology, and conjectures that the economy remains forever in a regime where fossil energy is an essential input. Consequently, the regulator defines its policy as if, at any time and for any income level, the representative household suffers damage from polluting emissions. We refer to the latter as a myopic regulator and denote by m the trajectories of the endogenous variables under the regulator's solution in this case.[9]

For a given initial condition $k_0 < \hat{k}$, the program is:

$$(\mathcal{P}^m): \quad \max_{\{c_t\}_0^\infty} \int_0^\infty e^{-\rho t} \left[\frac{\gamma}{2} c_t \left(2\bar{c} - c_t \right) - \theta k_t \right] dt$$

$$\dot{k}_t = (A - \delta) k_t - c_t \qquad (\lambda_t)$$

As shown in Appendix A.1, the problem admits explicit solutions for the optimal paths of the endogenous variables, if the potential productivity of investment is sufficiently large: $A - \delta > \rho$. This will be assumed for the remainder of the analysis. The endogenous variables move from their initial values to their asymptotic values according to the following expressions:

$$k_t^i = k_0 e^{-(A-\delta-\rho)t} + k_\infty^i \left(1 - e^{-(A-\delta-\rho)t} \right) \tag{3.1}$$

$$c_t^i = c_0^i e^{-(A-\delta-\rho)t} + c_\infty^i \left(1 - e^{-(A-\delta-\rho)t} \right) \tag{3.2}$$

where k_0 is predetermined, while c_0 and the asymptotic bundle (k_∞, c_∞) are endogenously determined according to the specific type of regulation. The generic superscript i denotes the solution corresponding to the regulation. For problem $(\mathcal{P}^m)$ under myopic regulation, the solution is (3.1)–(3.2) with $i = m$, and the steady state bundle

$$k_\infty^m = \frac{1}{A-\delta} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} \right) \tag{3.3}$$

$$c_\infty^m = \bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} \tag{3.4}$$

prevailing in the interesting case where the structural break does not occur by surprise, i.e. if $k_\infty^m < \hat{k}$. Myopic regulation would drive the economy toward this steady state whatever the initial capital endowment $k_0 < \hat{k}$. In particular this would also happen for k_0 very close but below $\hat{k}$, since the polluting emissions are judged excessive and environmental regulation is implemented to limit economic activity and income in order to reduce damage from polluting emissions. Here social welfare maximization neatly strikes the balance in the trade-off between material prosperity and environmental quality. Namely, the chosen long-run income is lower the larger the damage from polluting emissions due to consumption relative to its benefit, as measured by the ratio θ/γ.

The solution is admissible, in the sense that the myopic regulator chooses a path leading to a finite positive level of capital and consumption, only if the damage from polluting emissions relative to its productivity is bounded from above: $\theta < \bar{c}\gamma(A - \delta - \rho)$. Under these assumptions and in the interesting case where $k_\infty^m < \hat{k}$ we have the following result:

Proposition 1. *Under parameter values ensuring $k_0 < k_\infty^m < \hat{k}$, which we assume for the rest of the paper, convergence to the steady state is monotonic, and implies capital accumulation and consumption growth.*

Proof. See Appendix A.1. □

3.2. Brown regulation

In this scenario the regulator only cares about utility generated by consumption and does not take into account damage from polluting emissions in defining its policy. This scenario serves as a baseline case under laissez faire, against which the myopic and optimal regulation can be assessed. Additionally, this scenario represents the case of a small country contemplating domestic policies to mitigate climate change. The regulator in such a country does not deem that limiting its own emissions could affect global polluting emissions, which determine the damage it is concerned about.

In the absence of direct concern about own emissions, the potential switch to a service economy becomes irrelevant for defining policy. Technically, the program is simply a special case of the one under myopic regulation, where the sensitivity of utility to emissions is null, i.e. $\tilde{\theta} = 0$. Hence, the optimal paths (3.1) and (3.2) are still valid once one sets $i = b$ to denote brown regulation, and the steady state values for consumption and capital adjusted for $\tilde{\theta} = 0$ are:

$$k_\infty^b = \frac{\bar{c}}{A-\delta} \tag{3.5}$$

$$c_\infty^b = \bar{c} \tag{3.6}$$

Notice that this solution also applies in the case of a service economy, i.e. for the case of a capital endowment above the technology threshold level, as there is indeed no longer any damage.

[9] In the last paragraph of the Conclusion we discuss how this wording reflects the RtD policy stance.

Proposition 2. *Convergence to the steady state is monotonic, and implies capital accumulation and consumption growth. Initial consumption is lower when damage is ignored but the steady-state levels of both consumption and capital are higher, implying faster economic growth.*

The economic dynamics in this case clearly characterize our approach to development. It consists of a transitory improvement in material well-being, due to investment in capital. The accumulation process allows the economy to increase income until material consumption is satiated, i.e. there is no additional benefit from increasing consumption.

Comparing brown to myopic regulation we find that $c^m_\infty < c^b_\infty$ and $k^m_\infty < k^b_\infty$: because of its complementarity with polluting fossil inputs, capital exerts a negative effect on utility, so that the asymptotic level of capital, hence of consumption, is optimally chosen by the myopic regulator below that prevailing in a service economy (or chosen under brown regulation). The difference is proportional to θ, the sensitivity of utility with respect to emissions due to capital use under industrialization. Investment is high and consumption low relative to their optimal levels in the economy that is regulated to remain in the industrialized phase forever.[10] Even if the regulation that drives the dynamics of the economy does not account for emissions, it does not mean they do not occur: effective welfare is negatively affected by damage from polluting emissions.

For the remainder of the paper we assume that the parameter values satisfy $\hat{k} < k^b_\infty$, so that from the same endowment $k_0 < \hat{k}$ the myopic and the brown regulators would carry their economies to long-run equilibria characterized by a different technology.

3.3. Optimal regulation

Let us now consider the case where the structural break is possible, i.e. $\hat{k}$ finite and foreseen by the regulator. The service economy constitutes the second phase of economic development in the model with a structural break used by the regulator to define its policy. Suppose that this phase starts at time T. As the model is solved backward, we first characterize the dynamics in this service economy. Technically, the solution for this phase corresponds to the dynamics of brown regulation starting at time T with capital endowment $\hat{k}$. However, there are no polluting emissions, thus no implied damage to welfare over this phase.

For an initial condition $k_0 < \hat{k}$, the program is:

$$
\begin{aligned}
(\mathcal{P}^*):\quad & \max_{\{c_t\}_0^\infty, T} \int_0^T e^{-\rho t}\left[\frac{\gamma}{2}c_t\left(2\bar{c}-c_t\right)-\theta k_t\right]dt + \int_T^\infty e^{-\rho t}\frac{\gamma}{2}c_t\left(2\bar{c}-c_t\right)dt \\
& T:\quad k_T = \hat{k} \\
& \dot{k}_t = (A-\delta)k_t - c_t \qquad\qquad (\lambda_t)
\end{aligned}
$$

The solution that implies optimal structural change, occurring at date T, is characterized by the necessary first order conditions prevailing in the previous cases:[11]

(*i*) For the industrialization phase, i.e $\forall t \in [0, T)$ meanwhile $k_t < \hat{k}$, the dynamics resemble that obtained in Section 3.1, but for a different initial value of consumption c_0.

(*ii*) For the service economy phase, i.e. $\forall t \geq T$ once $k_t \geq \hat{k}$, the dynamics are similar to those presented in Section 3.2.

Moreover, the trajectory is optimal if it satisfies three additional boundary conditions:

(*iii*) The transversality condition:

$$\lim_{t\to\infty} e^{-\rho t}\lambda_t k_t = 0 \tag{3.7}$$

which implies that $\forall t \geq T$ the optimal paths are those given in Section 3.2 with $\hat{k}$ substituting for k_0 and $t-T$ for t in (3.1)–(3.2) with $i = b$.

(*iv*) The *target condition*, requiring sufficient capital accumulation during the industrialization phase, with k_t starting from k_0 and reaching $\hat{k}$ by date T:

$$\int_0^T \dot{k}_t\left(c_0\right)dt = \hat{k} - k_0 \tag{3.8}$$

where c_0 appears in brackets in the integrand to signify that instantaneous net investment $\dot{k}_t$ is a function of the initial consumption level, according to (*i*) above.

(*v*) The *junction condition*, which rules out any foreseeable discontinuity in the optimized current Hamiltonian function. From items (*i*) and (*ii*) above, the value of the Hamiltonian at date T, which we denote $\hat{H}$, is independent of c_0 and T, while the value of the Hamiltonian immediately before date T, which we denote H^i, depends on these two variables. The junction condition can be written as follows:

$$H^i\left(T, c_0\right) = \hat{H}. \tag{3.9}$$

Together the target condition (3.8) and the junction condition (3.9) determine the optimal values of the initial consumption c_0 and the date of structural change T. The following result establishes the condition for the existence and the uniqueness of the solution.

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[10] In fact $c^m_0 > c^b_0$ since (3.2), (3.4) and (3.6) imply $c^m_0 - c^b_0 = (\theta/\gamma)/(A-\delta)$.

[11] See (A.2)–(A.3) in Appendix A.1 with $\theta \neq 0$ for (*i*) and $\theta = 0$ for (*ii*).

Lemma 1. *There exists a unique bundle* (T^*, c_0^*) *satisfying conditions* (3.8) *and* (3.9) *if and only if*

$$k_0 < \Omega\,\hat{k} \tag{3.10}$$

with $\Omega \in (0,1)$ *defined by* (A.32) *in Appendix* A.2.

Proof. See Appendix A.2. □

The uniqueness of the solution follows from the fact that while the target condition implies a positive relation between c_0 and T, the junction condition implies a negative one.[12]

Proposition 3. *Under* (3.10)*, for* $k_0 < \hat{k}$ *the unique solution of program* ($\mathcal{P}^*$)*, that is the optimal trajectory with structural change, is defined by* T^* *and* c_0^* *solving* (3.8)–(3.9)*, and by the paths of consumption and capital that undergo two phases – an industrialization phase and a service economy phase – and converge to* $k_\infty^* = \bar{c}/(A-\delta)$ *and* $c_\infty^* = \bar{c}$*. It implies that*

(i) the consumption path increases suddenly upon structural change;
(ii) if the capital level that triggers a structural break would never be reached under myopic regulation (i.e $k_\infty^m < \hat{k}$*), then consumption is lower in the first phase (i.e* $c_t^* < c_t^m \;\; \forall t < T^*$*) but higher at steady state (i.e.* $c_\infty^* > c_\infty^m$*) than it would be under myopic regulation, implying stronger growth and temporarily higher polluting emissions.*

Proof. See Appendix A.2. □

Because of the technological discontinuity at date T^*, this optimal trajectory implies an upward jump in consumption upon structural change. To understand this, consider that consumption at each date is directly linked to the value of capital (λ). During industrialization investing in capital is valuable for two reasons. First, this allows future potential consumption to increase. Second, it allows to get closer to structural change to eventually avoid damage from polluting emissions. In the service economy this second component of the value of capital is nil. Therefore, upon date T^* the value of capital drops, and consequently consumption increases.

This can also be understood by inspecting the junction condition. At date T^* pollution emissions fall, instantly increasing the stream of current utility. Hence the value of capital, λ, and consumption must adjust. Since the optimized value of its right-hand-side $\hat{H}$ is constant, the consumption c_T and the corresponding λ_T are also constant. Hence, the junction condition can hold only if consumption on the trajectory up to date T, adjusts to reflect the damage from polluting emissions. Consider in particular $c_{T^-} \equiv \lim_{t\to T^-} c_t^*$. The current value of the Hamiltonian immediately before date T^* is a decreasing function of c_{T^-}.[13] We conclude that c_{T^-} must be reduced below c_T, to take into account the additional benefit accruing from investment in terms of permanent reduction of polluting emissions.[14]

We also find that if $k_\infty^m < \hat{k}$, the consumption path with structural change is initially below the one that would be chosen under myopic regulation, analyzed in Section 3.1. We show that the consumption paths under optimal and myopic regulation are isomorphic.[15] However, a larger amount of capital is accumulated in finite time along the trajectory with a structural break than in the one with myopic regulation. This is possible only if consumption paths are such that $c_t^* < c_t^m$ over the interval $t \in [0, T^*)$.

Our analysis hints at the opportunity of fostering economic development, to the extent that it makes it possible to access cleaner technologies, on top of increasing consumption. In this case, it is optimal to undergo a relatively large investment effort early on. Although it implies a relatively fast growth of polluting emissions, it eventually results in both higher consumption and lower pollution, as compared with the case of an economy indefinitely stuck in the early phase of development (industrialization). This provides a rationale for the RtD argument.

3.4. Numerical illustration

Let us now turn to some numerical illustrations to compare the trajectories under optimal regulation with those prevailing in each case of imperfect regulation. These comparisons aid in understanding the original rationale for the RtD put forward in this paper.

The numerical simulations are based on the set of parameters given in Table 1. In Appendix A.3, we explain how the values for parameters are determined. We do not wish to emphasize the empirical relevance of these simulations. Our highly stylized model should not be directly brought to the data to provide quantitative predictions. Rather, we use its calibrated numerical version to qualitatively illustrate and complement the results that have been obtained analytically.

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[12] Concerning the target condition, higher initial consumption implies lower investment and thus more time to reach the threshold level of capital ensuring the technological structural break. For the junction condition, the value of the Hamiltonian at the regime switching date depends on c_0 and T because they affect the consumption immediately before this date. They both tend to increase it, so that the junction condition implies a negative relation between c_0 and T.

[13] By definition $H^i(c_0,T) = \frac{\gamma}{2}c_t(2\bar{c}-c_t) - \theta k_t + \lambda_t\left[(A-\delta)k_t - c_t\right]$. Substituting for λ using (A.2) in Appendix A.1, we have $H^i(c_0,T) = \gamma\left[c_t^2 - (A-\delta)k_t c_t\right] + [\gamma(A-\delta)-\theta]\,k_t$. It follows that $\partial H^i(c_0,T)/\partial c_{T^-} = c_{T^-} - (A-\delta)\hat{k}$, which, according to (2.2), is negative since $\dot{k} > 0$ at date T^-.

[14] This is consistent with the literature on regime switching (Boucekkine et al., 2013) that shows that if the state variable level triggering the switch (here $\hat{k}$) is exogenous, this generally implies a discontinuity of the associated co-state variable. If, on the contrary, the level of the state variable can be freely chosen at the regime shift, its value (i.e. the co-state variable) is equal to the derivative of the optimized value function with respect to the state variable, which is continuous at the time of the regime switch. In our case, the state variable cannot be freely chosen, hence its co-state variable is no longer equal to the derivative of the optimized value function with respect to the state variable, thus there is no reason for the co-state variable to be continuous at that the time of the regime shift.

[15] See Appendix A.2. Compare Eq. (A.19) in particular to Eq. (3.2).

Table 1
Parameters for baseline simulation.

δ	.07	A	1/3	$\hat{k}$	114	ζ	3.37	b	9
ρ	.01	γ	.208	$\bar{c}$	31	$\tilde{\theta}$	.524	k_0	110

See Appendix A.3 for a detailed explanation.

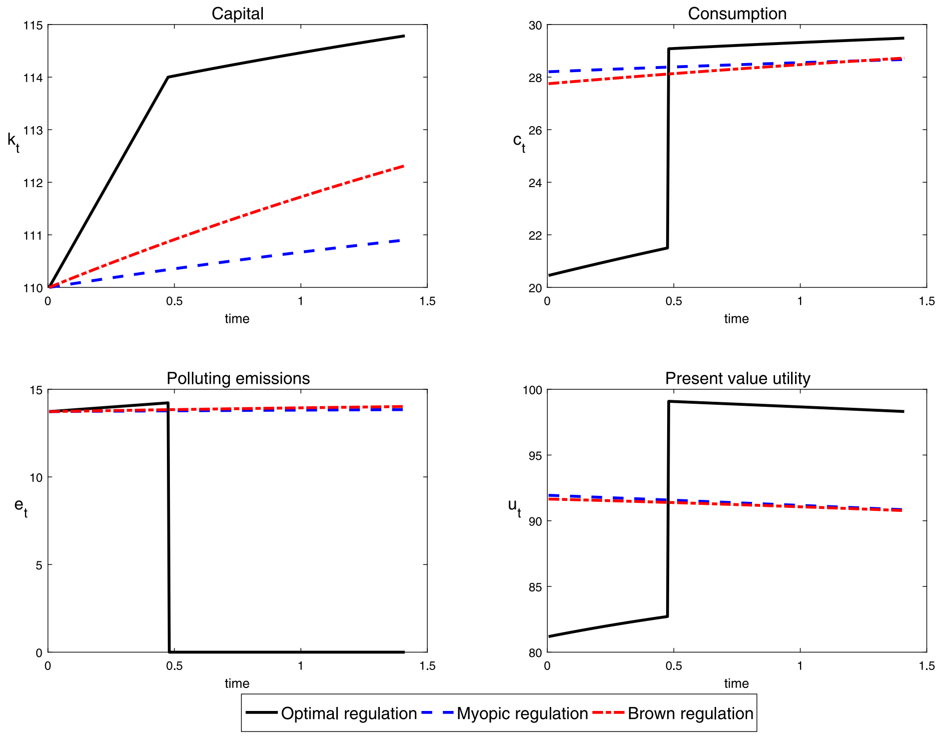

Fig. 1. Paths of main endogenous variables under the three regulation scenarios.

Fig. 1 represents the time path of capital, consumption, polluting emissions and the present value of the resulting stream of utility for the representative household, under the three different policy scenarios. The dashed lines refer to the case of myopic regulation, the dashed-dotted lines to the case of brown regulation, and the solid lines to optimal regulation.

By construction, the possibility of a technological structural break plays no role in determining the trajectories of capital and consumption under both myopic and brown regulation (in the interesting case $k^m_\infty < \hat{k}$ that we depict). The differences between the two outcomes are exclusively due to the different perceptions of the damage of polluting emissions. The upper panels of Fig. 1 illustrate what we obtained analytically in Section 3.2, that is, taking into account this damage leads to a slow-down in investment and consumption growth, with both capital and consumption monotonically converging to lower levels.

Notice that myopic regulation implies low investment and leads to a slow transition toward a steady state, with a permanent flow of polluting emissions affecting households. When the regulator considers the opportunity to permanently improve technology with respect to dependence on polluting fossil energy sources, undergoing structural change becomes a policy objective. In order to achieve it, the regulator fosters investment and capital accumulation, which implies lower consumption and higher emissions initially (see the lower left-hand-side panel and the upper panels of Fig. 1). The present value of the flow of utility is therefore chosen to be initially lower under pro-structural change than under myopic regulation. This can be considered a desirable intertemporal trade-off, to the extent that undergoing structural change makes it possible to attain permanently higher levels of consumption and lower levels of damage from polluting emissions, as illustrated in the last panel of Fig. 1.

Using the parameters in Table 1 to evaluate the expressions for welfare under each regulation regime,[16] we find that myopic regulation entails welfare 7.8% below what could be attained by optimally undergoing structural change. This outcome gives substance to the RtD argument.

[16] See Appendices A.1–A.2, namely expressions (A.14) and (A.36).

4. Pollution ceiling and the right to development argument

Given the experience with water and air pollution in urban areas in emerging economies such as China, an argument for slowing down economic growth in the early phases of development might rely on a policy objective of limiting pollution concentrations below critical levels. We extend the model in Section 3 to explore this potential mechanism. In contrast to what might be expected, in the case of cumulative pollution the above-mentioned policy objective reinforces the RtD argument.

We examine how the optimal policy is modified by the presence of potential catastrophic damage due to the accumulation of pollution above a threshold, as in the literature on the carbon ceiling (Chakravorty et al., 2006). We extend the model presented in Section 2 to introduce this public concern about the pollution stock.

The representative household considers the damage resulting from the stock of pollution exceeding a threshold $\overline{S}$ to be excessively high, so as to always prefer to make sure that:

$$S_t \leq \overline{S} \tag{4.1}$$

Polluting emissions e accumulate into a stock of pollution S, a stock that decays at a constant rate α. The law of motion of the stock of pollution is therefore:

$$\dot{S}_t = e_t - \alpha S_t \tag{4.2}$$

We restrict the analysis to the case $\alpha > \rho$. Taking into account efficient energy-capital use over the industrial phase, resulting from (2.1), and defining $\beta \equiv \zeta A/b$, we have:

$$\dot{S}_t = \begin{cases} \beta k_t - \alpha S_t & \forall k_t \leq \hat{k} \\ -\alpha S_t & \forall k_t > \hat{k} \end{cases} \tag{4.3}$$

The program for the extended model is equivalent to $(\mathcal{P}^*)$ under the additional constraints (4.1) and (4.3), for given initial stocks of pollution, S_0, and capital, k_0. Hereafter, we explain how to solve it, then compare the optimal path to that obtained in the absence of pollution ceiling.

The Lagrangian of the problem up to date T now takes into account the accumulation of pollution and the ceiling on its stock:

$$\mathcal{L}^i = \frac{\gamma}{2} c_t \left(2\bar{c} - c_t\right) - \theta k_t + \lambda_t \left[(A - \delta) k_t - c_t\right] - \mu_t \left(\beta k_t - \alpha S_t\right) + \nu \left(\overline{S} - S_t\right) \tag{4.4}$$

The first two terms reflect current utility, the third term the value of net investment in capital, the fourth term the value of the use of the pollution sink $\overline{S} - S_t$ (co-state variable μ), while the last term is the pollution ceiling constraint (multiplier ν).

Notice that emissions are nil once the economy is based on services, so that from date T onward the pollution stock monotonically declines toward zero at constant rate α. This implies $\mu_t = \nu = 0$ for $t > T$. Therefore, the ceiling on pollution might affect the program up to date T, but not later.

Under the law of motion of the pollution stock given by (4.3), if the pollution stock attains the threshold $\overline{S}$ then it can be stabilized at that level by holding the capital stock constant at $\tilde{k} = \alpha\overline{S}/\beta$. If stabilized at a level $\tilde{k} < \hat{k}$, the structural break in technology will not occur after the pollution level has reached the ceiling. We deduce that any optimal trajectory encompassing structural change will avoid pollution reaching $\overline{S}$ before date T. Hence, such a path will either imply $S_t < \overline{S}$ $\forall t$, or $S_t < \overline{S}$ $\forall t \neq T$ and $S_T = \overline{S}$ at T. We refer to the latter trajectories as the paths with a binding ceiling.

Let us define the unconstrained optimal path of capital accumulation as the one chosen in the absence of a pollution ceiling. In this case, the optimal trajectory of capital, from k_0 to k^*_∞ through $\hat{k}$ at date T^*, is characterized in Proposition 3. We denote by S^*_t the path of the pollution stock resulting from the path of capital accumulation k^*_t according to (4.3), up from S_0.[17] We define a threshold level of the initial pollution stock $\tilde{S}_0$ as:

$$\tilde{S}_0 = \overline{S} - \int_0^{T^*} \left(\beta k^*_t - \alpha S^*_t\right) dt \tag{4.5}$$

It follows that for any initial pollution stock $S_0 \leq \tilde{S}_0$ it is possible to follow the unconstrained optimal path characterized in Proposition 3, so that the additional damage due to pollution accumulation plays no role and $\nu = \mu_t = 0$ $\forall t \geq 0$. Instead, for a sufficiently high initial pollution level, and precisely for all $S_0 \in \left]\tilde{S}_0, \beta k_0/\alpha\right[$, the optimal path is affected, since following the accumulation path k^*_t would lead to excessive pollution $S^*_{T^*} > \overline{S}$.[18] In this case, the optimal trajectory of capital is modified, denoted $k^\diamond_t$ with the superscript $\diamond$ representing the solution for the case under a binding pollution ceiling.

Under binding ceiling, the solution paths for $t \geq T^\diamond$ are similar to those of the economy without a ceiling, with $T^\diamond$ substituting for T^*. As explained in detail in Appendix A.4, for $t < T^\diamond$ the first order conditions differ from those of Section 3.1 to take into account the additional stock variable, S_t, and the value of the pollution sink, μ_t. We obtain explicit solutions for the trajectories of all the variables, as a function of the three endogenous variables $(c^\diamond_0, T^\diamond, \mu^\diamond_0)$. The latter is defined by the three following conditions:

(i) the target condition (3.8);

[17] An expression for the time path of S^*_t is explicitly derived in Appendix A.4 as a function of c^*_0 and T^*.

[18] The upper bound on the initial stock of pollution $\beta k_0/\alpha$ corresponds to the situation such that the economy starts at the ceiling and cannot improve, staying there in a steady state.

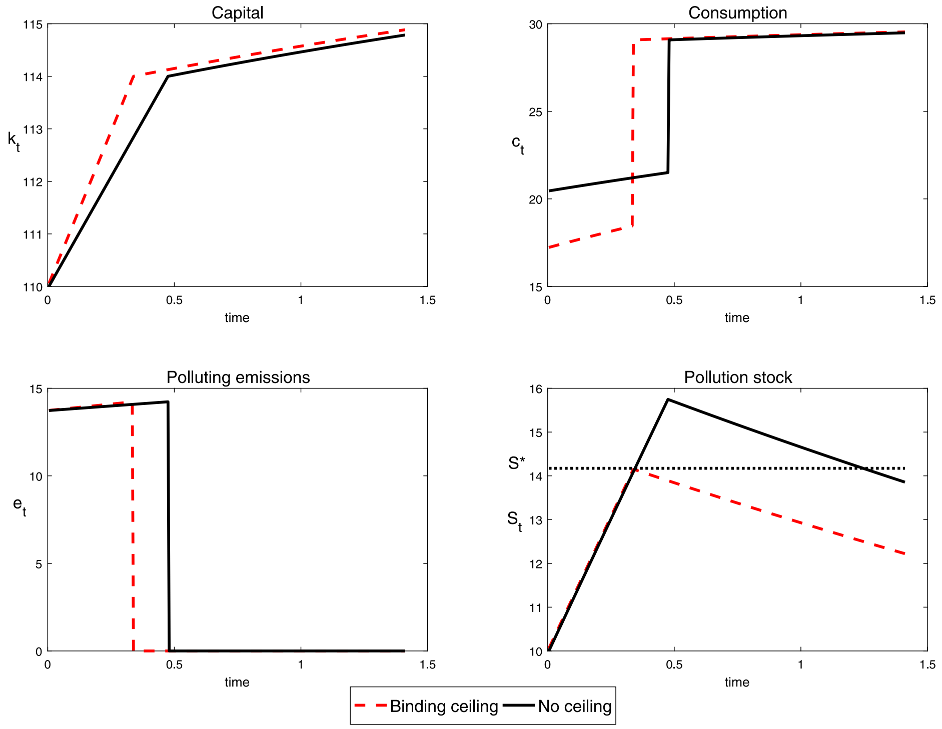

Fig. 2. Paths of main endogenous variables with and without a binding pollution ceiling.

(ii) the junction condition:

$$\mathcal{L}^i\left(c_0, T, \mu_0\right) = \hat{H}$$

(iii) the environmental compatibility condition:

$$S_T = \bar{S}$$

according to which, the pollution ceiling is attained precisely at the time of structural change.

The solution of the problem under a binding ceiling constraint is too complex to allow us to give an analytical interpretation of how the optimal trajectory of the economy is affected. We therefore present the solution of a numerical case, for parameter values in Table 1 and additional values compatible with positive initial consumption and binding ceiling.[19] Fig. 2 presents the paths of consumption, capital, emissions and pollution in the case with (dashed lines) and without (solid lines) a binding pollution ceiling. The following proposition summarizes our findings.

Proposition 4. *The investment in capital is higher under a binding pollution ceiling than without such a ceiling. The lower the ceiling, the earlier the optimal date of structural change. This choice implies a larger flow of polluting emissions and a smaller consumption flow during the (shorter) industrialization phase, pointing out the policy trade-off.*

To understand this result, consider the following. Under a binding cumulative pollution ceiling, capital accumulation is valuable for three reasons: (*i*) it increases future potential consumption; (*ii*) it allows the technological structural break to be attained to avoid further damage from polluting emissions; (*iii*) and it allows technological structural change to be attained to overcome the scarcity problem of the pollution sink. In a service economy (or under brown regulation) only the first effect is accounted for. During industrialization, without a binding ceiling the third motive is irrelevant and the solution is characterized in Proposition 3. Hence, as compared with the latter case, the optimal regulation under a binding pollution ceiling implies a greater value of additional capital (i.e. the additional motive (*iii*) above). It therefore calls for higher investment (thus lower consumption) and faster growth.

This result is peculiar and deserves an additional explanation. Pollution is more costly in the case with a binding ceiling than in the case described in Section 3.3. It seems reasonable to expect that the solution would imply lower polluting emissions and less

[19] Specifically $\alpha = .13667$, $S_0 = 10$ and $\bar{S} = 14.1719$, 10% lower that the peak stock of pollution under the accumulation path k_t^*. The resulting levels of initial consumption c_0° and date of structural change T° are about 16% and 19% lower than in the case without a binding ceiling.

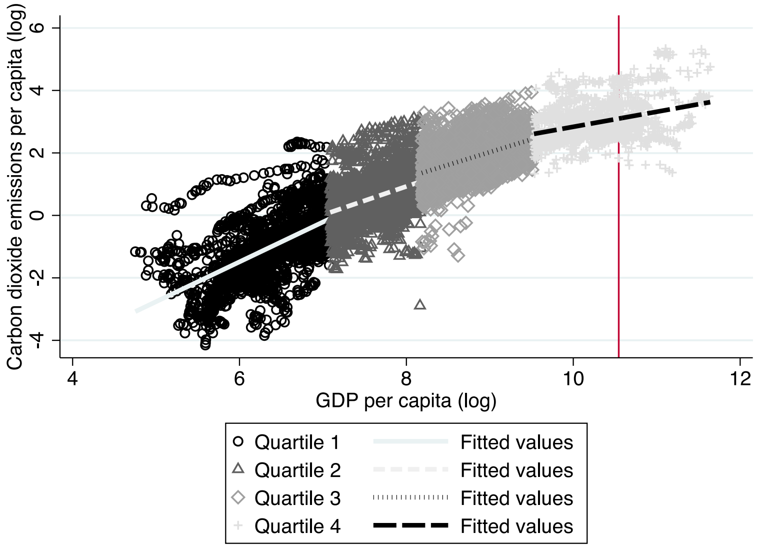

Fig. 3. Scatter plot of CO_2 per capita on GDP per capita for the full country sample 1960–2014. The vertical line at 37,979 2010 US dollars.

pollution over the industrialization phase. Instead, we find the opposite. The reason is that the more pressing problem of pollution can be coped with either by halting growth to stabilize emissions and the pollution stock or opting for a less polluting technology. In the framework where the RtD argument holds, as presented in this paper, the only way to make the technology less polluting is by developing the economy to a level where it will be based on services. This is optimal and is done by fostering investment to increase output, and incidentally polluting emissions, at least during an initial phase of industrialization. We conclude that problems arising from cumulative pollution reinforce the RtD argument, that is they increase the stakes of economic development.

5. Empirical evidence

In our framework, the rationale for the RtD argument hinges on the changing role of fossil fuels over the phases of economic development. We are therefore interested in the relationship between economic development and the use of fossil resources. To explore this relationship empirically, we consider income per capita as an index of economic development, and CO_2 emissions per capita as an index of fossil resource use (the correlation coefficient between CO_2 emissions per capita and fossil resource use is equal to 0.78 (see also Figs. 4 and 5 in Appendix A.5).

Data

Our data encompasses an unbalanced panel of 159 countries from 1970 to 2014, and a sub-sample with a balanced panel of 131 countries between 1983 and 2014, both retrieved from the World Development Indicator database.[20] Working with such a large set of countries has the main advantage of reducing sample selection bias due to the elimination of countries with missing data, to the extent that the latter systematically differ from those that have complete observations. We also employed different methodologies on the smaller balanced panel to verify consistency of the results. Conclusions of the empirical analysis are robust to alternative methodologies.

The variables we consider are presented in Table 4 in Appendix A.5, which reports descriptive statistics and correlation indices for the unbalanced panel. The variables reported are GDP per capita (constant 2010 US dollars, GDP/CAP), carbon dioxide emissions in kt per capita (CO_2/CAP), the total population (POP) and the composition of population by age in % of total population (below 14 years old POP<14, between 15 and 64 years old POP 15-64), the value added of service sectors in % of GDP (VA SERV), the valued added of industry in % of GDP (VA INDUS) and the imports of goods and services in % of GDP (IMPORTS).

Descriptive statistics

Our aim is to verify the empirical relevance of the following hypothesis: the reduction of the role of fossil resources for economic growth as the economy develops. This is a mild version of the hypothesis assumed in the theoretical part of the paper.

Evidence of an inverted U-shaped relationship between per capita income and CO_2 emissions, as a proxy for fossil resource use, would support this hypothesis. Our analysis is related to the large body of literature on the empirical relevance of the EKC hypothesis, initiated by Grossman and Krueger (1995). The inverted U-shaped relationship between per capita income and pollution has been extensively documented in the literature. According to Uchiyama (2016), the peak of the inverted U-shaped relation between CO_2 emissions and aggregate income was estimated at about 30,000 2005 US dollars based on a panel of 171 countries from 1960–2010.

[20] For the list of countries in the unbalanced panel see Appendix A.5.

Table 2
Results from decile regressions.

Dep. variable $\ln CO_2/CAP$	Decile 1[a]	Decile 10
lnGDP/CAP	1.0214***	0.1807**
	(0.1221)	(0.0699)
Observations	570	570
R-squared	0.4583	0.2692
Number of countries	28	28

Standard errors in parentheses; *** $p < .01$, ** $p < .05$, * $p < .1$.
[a] First decile of GDP/CAP, representing 10% of total observations with the lowest GDP/CAP.

We therefore adopt a progressive approach in exploring this hypothesis, starting from descriptive statistics and moving on to static econometric methods. As a robustness check we employ a dynamic econometric approach to deal with potential endogeneity issues.

If the foundation for our hypothesis lies in the changing role of fossil energy sources over the phases of development, then the fact that structural change of an economy is a long-term process makes it difficult to identify an elasticity of CO_2 emissions to GDP in early stages equal to 1 and then equal to 0 in later stages with historical data, as it is formally assumed in our theoretical model. However, it is possible to test the hypothesis of a structural break or discontinuity using existing data. If this milder hypothesis is correct, we expect to estimate a positive relationship between carbon dioxide emissions and income for both developing and developed countries, but close to unity for the former, and significantly lower (close to 0, or possibly no association) for the latter.

The data show a positive relationship between CO_2 emissions and aggregate income. The correlation index is equal to 0.715 (see Table 4 in Appendix A.5). However the relationship may not be linear, as the scatter plot in Fig. 3 suggests.

Moreover, our sample data corroborates the evidence for the irrelevance of leapfrogging in energy intensity hypothesis in van Benthem (2015). In fact, as shown in Fig. 6 in Appendix A.5 the relationship between CO_2 emissions and aggregate income is stable over time, despite the improvement in energy technology.

Static analysis with FE and FGLS models

In the econometric analysis, we first specify the following fixed effects (FE) model to test the relationship between carbon dioxide emissions per capita and GDP per capita:[21]

$$\ln e_{it} = \eta_1 \ln y_{it} + \eta_2 V_{it} + \eta_3 X_{it} + \upsilon_i + corr_t + \epsilon_{it} \tag{5.1}$$

where e_{it} denotes CO_2/CAP and y_{it} GDP/CAP of country i in year t. To control for sectoral composition, we introduce a vector V_{it} including VA INDUS and VA SERV (agriculture being the reference category) as well as IMPORTS. X_{it} is a set of demographic variables: POP, POP<14, POP 15-64 (the share of population above 65 being the reference category).[22] Finally, υ_i is a country fixed effect capturing a time-invariant country specific category, $corr_t$ is a time fixed effect and ϵ_{it} is the error term.

Results are presented in column (1) of Table 5 in Appendix A.6. The elasticity of CO_2 emissions with respect to GDP is estimated significantly positive and equal to 0.72, in line with the literature (e.g. Csereklyei et al., 2016).

Examining Fig. 3, the relationship between income and emissions appears non-linear. To test for this potential non-linearity, we introduce a squared term of income per capita into the previous Eq. (5.1):

$$\ln e_{it} = \eta'_1 \ln y_{it} + \eta'_2 (\ln y_{it})^2 + \eta'_3 V_{it} + \eta'_4 X_{it} + \upsilon'_i + corr'_t + \epsilon'_{it} \tag{5.2}$$

Results are shown in column (2) of Table 5 in Appendix A.6. The estimated coefficient of log GDP per capita is still positive, but that of its squared value is negative and significant, pointing to a non-linear relationship. The estimated threshold of GDP per capita beyond which CO_2 emissions fall with income ($\exp(-\eta'_1/(2\eta'_2))$) is out of sample. In other words, our results do not show evidence for a bell-shaped relationship between the two variables, but confirm its non-linearity, implying that the correlation between CO_2 emissions and GDP declines with income per capita.

We also check for the presence of a non-linear relationship between CO_2 emissions and income per capita, by estimating Eq. (5.1) by income deciles. This method allows us to estimate the effect of these explanatory variables on the entire spectrum of the distribution of CO_2 emissions across the pooled data set. Since the slope coefficients are allowed to vary across the chosen quintiles, the method is less restrictive than the OLS method previously applied.

Importantly for our analysis, the estimated elasticities of CO_2 emissions with respect to income per capita, though always positive, are considerably lower in high income deciles than in lower income deciles. This elasticity is more than 18 times higher in the first

[21] The two common models for panel data analysis are the FE model and the random-effects model (RE). The time-invariant variable $corr_t$ is assumed to be uncorrelated with the other explanatory variables in the RE approach, but they may be correlated in the FE model. A Hausman test should be conducted to choose between the FE and RE models. The calculated test statistic was 112.57, rejecting the null hypothesis that individual effects are uncorrelated with the other explanatory variables at the 1% significance level. Hence, the fixed effects model is compatible with the rest of our study.

[22] Control variables are chosen following literature such as Deichmann et al. (2019).

Table 3
Results of the Panel Threshold Regression model.

Model with lnGDP/CAP	Coefficients
GDP/CAP less or equal to Threshold	0.8594***
	(0.0138)
GDP/CAP greater than Threshold	0.8276***
	(0.0135)
Threshold effect test (bootstrap = 10000):	
Threshold	10.5448
Fstat	232.41
P-value	0.0000
Crit10	73.429
Crit 5	86.7697
Crit 1	116.9483
Observations	3870
R squared	0.5081
Number of countries	129
Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1	

than in the last decile, according to the result reported in Table 2. As can be clearly seen in Fig. 3 the estimated elasticity of CO_2 emissions with respect to aggregate income falls as the sample of observations shifts up the ladder of income quartiles. It is possible to test the homogeneity of parameters with a Chow test. The null hypothesis is the homogeneity between sub-groups. The computed Fisher test statistic is equal to 546.4 and largely exceeds the theoretical value. We can reject the null hypothesis, and state that the estimated coefficients are heterogeneous across sub-groups.

In order to ensure the validity of our estimators, we estimate the model employing the feasible generalized least squares (FGLS) method, which can overcome heteroscedasticity and autocorrelation problems.[23] Results are shown in column (3) of Table 5 in Appendix A.6. The nature of the results does not differ from what was obtained previously. There seems to be a non-linear relationship between CO_2 emissions and income.

Static model with non-linearity using a Panel Threshold Regression model

It is also possible to check for non-linearities using a Panel Threshold Regression (PTR) model (Hansen, 1999). This method allows for the relationship between income and CO_2 emissions to vary non-linearly across sub-groups of observations, without imposing a specific form for the non-linearity. It tests for the presence of threshold levels of the explanatory variable, such that its impact on the dependent variable significantly differs. In the end PTR allows us to identify a partition of income observations characterized by homogeneous elasticity of CO_2 with respect to income. The main limit of this method is that it requires the use of a balanced panel, implying the loss of some – mostly poor – countries from the sample. Our aim is to verify whether the estimated elasticity differs between poorer and richer countries, and to determine the relevant threshold income level. We estimate the following PTR specification:

$$\ln e_{it} = \eta_1'' \ln y_{it} \cdot I\left(y_{it} \leqslant \hat{y}\right) + \eta_2'' \ln y_{it} \cdot I\left(y_{it} > \hat{y}\right) + \eta_3'' V_{it} + \eta_4'' X_{it} + v_i'' + \epsilon_{it}'' \tag{5.3}$$

$I(.)$ is the indicator function specifying the position of the observation relative to the endogenous threshold level of per capita income $\hat{y}$. The error term ϵ_{it}'' allows for conditional heteroscedasticity and weak dependence.

The first step in the PRT procedure consists of testing for the existence of a threshold. Following Hansen (1999) we estimated the model, allowing for a threshold. Before estimating a PTR model, the first step consists of determining the number of groups or testing for the existence of threshold(s) using a $Fstat$. When testing for the presence of a single threshold, we found that the Fstat is significant, with a very low bootstrap P-value. This provides the first evidence that the relationship between per capita carbon dioxide emissions and per capita income is not linear. The results of these tests and the estimated threshold value $\hat{y}$ for variable GDP per capita are reported in Table 3.

The estimations of the value of the threshold $\ln \hat{y}$ show a mean value at 10.5448. The asymptotic confidence interval for the threshold is narrow, i.e. [10.5306 10.5695], indicating little uncertainty about the division of countries in two groups according to their y relative to $\hat{y}$. More precisely, observations characterized by income per person above $\hat{y} = e^{10.5448}$ = 37,979 2010 US dollars are part of the set of high-income observations, characterized by relatively low elasticity of CO_2 emissions with respect to income.

After demonstrating the existence of a threshold and determining its value, our results corroborate previous estimates of CO_2 emissions elasticity with respect to GDP. Regardless of the model used, our estimates suggest that the elasticity of CO_2 emissions with respect to income is positive for both classes of observations, ranging from 0.86 to 0.83. This means that when GDP per capita

[23] The OLS estimation will determine statistically inefficient coefficient estimates in the presence of heteroscedasticity and autocorrelation, which are common in panel data. Thus, we employ the Modified Wald and Wooldrige tests to verify these last two hypotheses. The null hypothesis of the Modified Wald test is that the variance of the error terms is constant. The null hypothesis of the Wooldrige test is that the errors are homoscedastic. The value of Chi2 for the modified Wald test for groupwise heteroscedasticity is equal to 5.510E+05 and the Wooldridge test for autocorrelation in panel data show a F(1, 154) statistic equal to 333.855. Both null hypotheses are rejected at the one percent significance level. Results indicate that heteroscedasticity and autocorrelation problems exist in our data.

increases by 1%, carbon dioxide emissions increase more in countries with a level of per capita income below the threshold value of $\hat{y} = 37{,}979$ 2010 US dollars. The difference between the estimated elasticities does not appear important in size. This is probably because a disproportionately high share of poor countries is removed from the sample in moving from the full unbalanced sample to the sub-sample for the balanced panel data set. Yet, the difference between the estimated elasticities is statistically significant, a result that, on top of confirming the non-linearity of the relationship between CO_2 and GDP, seems in line with the representation of structural change used in our theoretical model.

Our finding is in line with the empirical literature. Apart from studies estimating the validity of the EKC for CO_2 (Uchiyama, 2016), our results complement those focusing on the role of energy for economic development.[24]

Before concluding, we observe that the discontinuity in the CO_2 intensity of GDP is also estimated using the a dynamic analysis as a robustness test (see Appendix A.7). There are three sources of potential biases, with one of them due to simultaneity. The methodology in Arellano and Bond (1991) allows us to address the simultaneity bias between CO_2 emissions and income using the lagged values of the latter as an instrument. We can also introduce lagged values of the dependent variable as explanatory variables. The results of this procedure are presented in Table 6 in Appendix A.7. They confirm the presence of a discontinuity in the correlation between aggregate income and CO_2 emissions. Unfortunately, we cannot control for all potential endogeneity issues using aggregate data. In particular, concerning omitted variables we are unable to control for the co-evolution of energy prices and regulation.

6. Conclusion

The Right-to-Development reflects the concern for developing countries about the potential impact of climate action on their prospects of sustained development. It resulted in the recognition by the UN that there should be “common but differentiated responsibilities and respective capabilities, in the light of different national circumstances, and the right to development, in the context of sustainable development and efforts to eradicate poverty”.[25]

We show that it may make sense to let the economy grow beyond the steady state that would be chosen by a myopic regulator, who ignores the possibility of a technological breakthrough reducing dependence on polluting energy sources. By allowing emissions to be momentarily above the maximum level set under myopic regulation, the economy reaps the benefits of such a structural change, ultimately eliminating polluting emissions. This *pro-growth* and *anti-environmental regulation* argument rests on the comparison of the trajectories obtained under myopic regulation and optimal regulation. The expectation of such a technological breakthrough provides a rationale for the Right-to-Development argument in a closed economy context.

We also investigate whether a similar argument still applies in the case where the pollution stock must be kept under or at a ceiling in order to avoid catastrophic outcomes. We find that it is optimal to further accelerate capital accumulation and growth in order to benefit from a permanent shift to the cleaner technology since the stakes from structural change are higher. Hence, the Right-to-Development argument is reinforced when the policy objective is to cap the stock of pollution.

All these results are based on strong assumptions. In particular, we assume the existence of a threshold for the technological structural break. We compare the experience across countries and show that the reliance on fossil fuels (and thus CO_2 emissions) diminishes when economic development is sufficiently high. This result points to the empirical relevance of the crucial assumption. Indeed, the representation of technological discontinuity in our model pushes the qualitative features of our empirical results to the extreme. Yet, the mechanisms underpinning the Right-to-Development argument are operational at least from a qualitative perspective for a weaker discontinuity.

In addition, our results are obtained in a closed economy setting. Right-to Development is however related to bargaining in international environmental agreements. Hence, one may want to consider the trade-off highlighted by our analysis in an international context. First, if we introduce the potential for a cleaner technology at a cost, it would inhibit growth in our model, but a combination of faster and cleaner growth could still be possible if these costs were to be financed from abroad. This could be a worthwhile extension of this paper. Second, one may want to revisit (Bretschger and Vinogradova, 2015) in our framework, to verify whether recognizing the right of developing countries to increase pollution before stabilizing their carbon emissions, is – in our context – a necessary condition to convince them to voluntarily join a global climate policy.

The aim of this paper is to clarify one possible argument for the Right-to-Development. Since the Right-to-Development is a policy stance in the characterization of climate policies, what the paper proposes is a clear-cut representation of the causal nexus underpinning the rationale: prioritize economic development over environmental regulation, since the former brings along a structural break freeing the economy from its dependency on polluting energy sources. In other words, the model and empirical analysis presented in this paper make a specific stance in the policy discourse explicit. Accordingly, we adopt a wording coherent

[24] Jakob et al. (2012) analyzed a sample of 51 countries over the period 1971–2005, and found that economic catch-up is accompanied by above-average growth in final energy consumption in most sectors and total CO_2 emissions, while in industrialized countries, economic growth is partially decoupled from energy consumption. Bretschger (2015) analyzed a sample of 37 countries over the period 1975–2009 to establish that in OECD economies decreasing energy use seems to foster capital accumulation and growth. Lechthaler (2017) extended the sample to 117 countries over the period 1973–2007 and found that in emerging economies energy use drives capital accumulation, then growth. Deichmann et al. (2019) considered 37 countries over the period 1990–2014 and showed that the energy intensity falls with income, but not much beyond 5,000 US dollars per capita, and using index decomposition, that structural change is relatively important for lower income levels. Csereklyei et al. (2016) analyzed 99 countries over the period 1971–2010 and found that decreases in energy intensity were positively related to economic growth, while the energy-capital ratio behaved similar to energy intensity.

[25] Ministerial Declaration of the Group of 77 (November 2021, paragraph 102).

with such a policy stance. However, our framework and analysis can serve the discourse of the opposite policy stance. In fact, in the case where the structural break does not exist in reality, what we referred to as optimal regulation represents in fact the dangerous case of a *green-growth dream regulation*, one where the regulator decides the investment policy based on the incorrect presumption of a technological structural break, eventually resulting in disappointment and leading the economy to ruin and a catastrophic outcome. This final remark calls for further research on the empirical relevance of a technological structural break significantly reducing the dependence of aggregate economic activity on polluting energy sources.

CRediT authorship contribution statement

Dorothée Charlier: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Aude Pommeret:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Francesco Ricci:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing.

Appendix A. Appendices

A.1. Resolution of the program in Section 3.1

The current value Hamiltonian of problem ($\mathcal{P}^i$) with $i = m$ in the case of myopic regulation, and $i = b$ and $\tilde{\theta} = 0$ in case of brown regulation is:

$$H^i = \frac{\gamma}{2} c_t \left(2\bar{c} - c_t\right) - \theta k_t + \lambda_t \left[(A-\delta)\, k_t - c_t\right] \tag{A.1}$$

with initial condition k_0 given and no possibility of overcoming industrialization $\hat{k} = \infty$. We restrict attention to the case $c_t \leq \bar{c}$ $\forall t \geq 0$.

The necessary conditions for the solution of this problem are $\partial H^i/\partial c = 0$ and $\dot{\lambda} = \rho\lambda - \partial H^i/\partial k$. They are:

$$\gamma(\bar{c} - c_t) = \lambda_t \qquad \Leftrightarrow \qquad c_t = \bar{c} - \frac{\lambda_t}{\gamma} \tag{A.2}$$

$$\dot{\lambda}_t = \theta - (A - \delta - \rho)\, \lambda_t \tag{A.3}$$

This differential equation can be solved to obtain:[26]

$$\lambda_t = \gamma \left(\bar{c} - c_0\right) e^{-(A-\delta-\rho)t} + \frac{\theta}{A-\delta-\rho} \left(1 - e^{-(A-\delta-\rho)t}\right) \tag{A.4}$$

Using this back into (A.2), we have:

$$c_t = \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) \left(1 - e^{-(A-\delta-\rho)t}\right) + c_0 e^{-(A-\delta-\rho)t} \tag{A.5}$$

which can be inserted into (2.2) to get:

$$\dot{k}_t - (A-\delta)\, k_t = -\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) \left(1 - e^{-(A-\delta-\rho)t}\right) - c_0 e^{-(A-\delta-\rho)t} \tag{A.6}$$

This differential equation can be integrated to obtain:

$$k_t = \frac{1}{A-\delta} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) - \frac{1}{2(A-\delta)-\rho} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right) e^{-(A-\delta-\rho)t} + \bar{x} e^{(A-\delta)t} \tag{A.7}$$

The transversality condition (3.7) with (A.4) and (A.7) imply $\bar{x} = 0$. Hence, we can write the optimal capital stock at any date as a function of the initial level of consumption c_0:

$$k_t = \frac{1}{A-\delta} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) - \frac{1}{2(A-\delta)-\rho} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right) e^{-(A-\delta-\rho)t} \tag{A.8}$$

Finally, the initial condition k_0 pins down the optimal initial level of consumption:

$$c_0^i = \bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - \frac{2\,(A-\delta)-\rho}{A-\delta} \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - (A-\delta)k_0\right) \tag{A.9}$$

Use this back into (A.8), (A.4) and (A.5), we deduce (A.10)–(A.12), thus the steady state characterized by (3.3)–(3.4). Notice that $c_0 < \bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}$ if and only if $k_0 < k^i_\infty$. In this case, the economy asymptotically converges to a steady state by accumulating capital over time.

$$k_t^i = \frac{1}{A-\delta} \left(\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) \left(1 - e^{-(A-\delta-\rho)t}\right) + (A-\delta)\, k_0 e^{-(A-\delta-\rho)t}\right) \tag{A.10}$$

[26] Define $z_t \equiv \lambda_t e^{(A-\delta-\rho)t}$, so that $\dot{z}_t = \theta e^{(A-\delta-\rho)t}$. Integrate the latter to get $z_t = \bar{z} + e^{(A-\delta-\rho)t}\theta/(A-\delta-\rho)$, then use the definition of z to get $\lambda_t = \bar{z}e^{-(A-\delta-\rho)t} + \theta/(A-\delta-\rho)$. Finally, pin down $\bar{z}$ by using λ_0 at date $t = 0$ in (A.2), to write $\gamma(\bar{c} - c_0) = \bar{z} + \theta/(A-\delta-\rho)$.

$$\lambda_t^i = \frac{\theta/\gamma}{A-\delta-\rho} + \gamma \frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - (A-\delta)k_0\right)e^{-(A-\delta-\rho)t} \tag{A.11}$$

$$c_t^i = \bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - \frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - (A-\delta)k_0\right)e^{-(A-\delta-\rho)t} \tag{A.12}$$

Welfare (A.14) is computed using (A.10) and (A.12) in ($\mathcal{P}^m$): The resulting welfare is:

$$\begin{aligned} W^i \;=\; & \frac{1}{\rho}\left(\gamma c_\infty^i\left(\bar{c} - \frac{c_\infty^i}{2}\right) - \theta k_\infty^i\right) + \frac{\theta}{A-\delta}\left(k_\infty^i - k_0\right) \\ & - (2(A-\delta)-\rho)\gamma\left(k_\infty^i - k_0\right)\left(k_\infty^b - \frac{1}{2}\left(k_\infty^i - k_0\right)\right) \end{aligned} \tag{A.13}$$

Welfare under myopic regulation, W^m, is obtained for k_∞^i and c_∞^i defined by (3.3) and (3.4) for $i = m$. This expression is also valid for the service economy, W^s, with k_∞^i and c_∞^i defined by (3.5) and (3.6) and $\theta = 0$.

A.2. Proof of Lemma 1 and Proposition 3

We first show that the target condition implies a positive relationship between T and c_0, while the junction condition implies a negative relationship between these two variables. In fact, for a given k_0 the higher c_0 the lower investment, and the longer it takes to reach $\hat{k}$ during the industrialization phase, thus the later T is, and vice versa. The junction condition, instead, pins down a unique value for the consumption right before T, which can be reached later (i.e. increasing T) by choosing a lower c_0, during the industrialization phase, and vice versa. Condition (3.10) establishes that, for $T = 0$ the initial level of consumption implied by the junction condition is larger than that implied by the target condition. We then show that the c_0 implied by the junction condition becomes nil for a finite date of the structural break, and for that date the c_0 implied by the target condition is positive. Hence the two conditions define two schedules that cross only once for a finite date T and positive c_0.

Given $k_0 < \hat{k}$, the solution of ($\mathcal{P}^*$) that implies optimal structural change, occurring at date T, is characterized by the necessary conditions (A.2)–(A.3) for all $t \le T$, and the system but with $\theta = 0$ for all $t > T$. The trajectory is optimal if it satisfies the additional conditions:

(iv) The *target condition* (3.8), which implicitly defines c_0 as a function of T according to:

$$F\left(T, c_0\right) \equiv \int_0^T \dot{k}_t(c_0)dt - (\hat{k} - k_0) = 0 \tag{A.14}$$

(v) The *junction condition* of the Hamiltonians (3.9), which implicitly defines c_0 as a function of T according to:

$$G\left(T, c_0\right) \equiv H^i\left(T, c_0\right) - \hat{H} = 0 \tag{A.15}$$

Characterization of the target condition (A.14). During the industrial phase the solution satisfies (A.2), (2.2) and (A.3), thus capital accumulates according to (A.7). Setting this expression for $t = 0$ equal to k_0 to obtain $\bar{x}$ leads to:

$$\bar{x} = k_0 - \left(\frac{A-\delta-\rho}{(2(A-\delta)-\rho)(A-\delta)}\right)\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right) - \frac{1}{2(A-\delta)-\rho}c_0 \tag{A.16}$$

Substituting for $\bar{x}$ in (A.7), the capital path $\forall t \in [0, T)$ is

$$\begin{aligned} k_t \;=\; & e^{(A-\delta)t}\left(k_0 + \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right)\left(\frac{\left(1-e^{-(A-\delta-\rho)t}\right)}{2(A-\delta)-\rho} - \frac{\left(1-e^{-(A-\delta)t}\right)}{A-\delta}\right)\right) \\ & - e^{(A-\delta)t}\left(\frac{c_0}{2(A-\delta)-\rho}\left(1-e^{-(A-\delta-\rho)t}\right)\right) \end{aligned} \tag{A.17}$$

from which we deduce

$$\begin{aligned} k_t^* =\; & k_\infty^m + \frac{e^{(A-\delta)t}}{2(A-\delta)-\rho}\left[\left(c_\infty^m - c_0^*\right) - \left(k_\infty^m - k_0\right)(2(A-\delta)-\rho)\right] \\ & - \left(c_\infty^m - c_0^*\right)\frac{e^{-(A-\delta-\rho)t}}{2(A-\delta)-\rho} \end{aligned} \tag{A.18}$$

$$c_t^* = c_0^* e^{-(A-\delta-\rho)t} + c_\infty^m\left(1 - e^{-(A-\delta-\rho)t}\right) \tag{A.19}$$

with k_∞^m and c_∞^m defined in (3.3) and (3.4).

Substituting $\hat{k}$ for k_t in (A.17) the target condition can be written as:

$$F(T, c_0) = F_1(c_0)e^{(A-\delta)T} + F_2(c_0)e^{-(A-\delta-\rho)T} + F_3 = 0 \tag{A.20}$$

where we define

$$F_1(c_0) = \left(k_0 - \frac{\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}}{A-\delta} + \frac{1}{2(A-\delta)-\rho}\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right)\right) \tag{A.21}$$

$$F_2(c_0) = -\frac{1}{2(A-\delta)-\rho}\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right) \tag{A.22}$$

$$F_3 = \frac{\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}}{A-\delta} - \hat{k} \tag{A.23}$$

In the interesting case $k_0 < k^m_\infty < \hat{k}$, the terms F_1, F_2, F_3 can be signed. Using (3.3) we have $F_3 = k^m_\infty - \hat{k} < 0$. Moreover from (3.4) $F_2(c_0) < 0$ for $c_0 < c^m_\infty$. This is the case because on the one hand we trivially have that $c^m_0 < c^m_\infty$, and on the other hand $c_0 < c^m_0$. In fact, the optimal policy implies attaining a larger capital stock in finite time, than the capital stock toward which the economy would asymptotically converge in the special case of Section 3.1, i.e. $\hat{k} > k^m_\infty$. It therefore requires initially saving a larger amount of income, that is choosing an optimal c_0 below the one given by (A.9). Finally, $F_1(c_0) > 0$, because it must balance the negative terms in function (A.20).

We therefore have the following:

$$\frac{\partial F}{\partial T} = (A-\delta)\, F_1(c_0)e^{(A-\delta)T} - (A-\delta-\rho)\, F_2(c_0)e^{-(A-\delta-\rho)T} > 0$$

and

$$\frac{\partial F}{\partial c_0} = \frac{1}{2(A-\delta)-\rho}\left(e^{-(A-\delta-\rho)T} - e^{(A-\delta)T}\right) \le 0 \tag{A.24}$$

with equality holding only for $T = 0$.

Along the optimal development path encompassing structural change, the *target condition* implies a positive relationship between the two endogenous variables T and c_0:

$$\left.\frac{dc_0}{dT}\right|_{F=0} = -\frac{\partial F/\partial T}{\partial F/\partial c_0} > 0. \tag{A.25}$$

Characterization of the junction condition (A.15). The transversality condition (3.7) allows us to pin down the values of consumption and of the shadow price of capital at date T in the ongoing program for the service economy that correspond to the analysis of the brown economy, but with no damage when computing welfare, as analyzed in Section 3.2 and Appendix A.1. The solution implies that at date T the level of consumption, which we denote $\hat{c}$, is given by c_0 in (A.9) for $\theta = 0$, and the value of capital, denoted by $\hat{\lambda}$, by λ_0 obtained with (A.4) and (A.9) for $\theta = 0$, substituting $\hat{k}$ for k_0 in the two expressions. Doing so we determine the value of $\hat{H}$ in condition (A.15) from (A.1) with $\theta = 0$ as

$$\begin{aligned}\hat{H} &= \frac{\gamma}{2}\hat{c}\,(2\bar{c}-\hat{c}) + \hat{\lambda}\left((A-\delta)\hat{k} - \hat{c}\right)\\ &= \frac{\gamma}{2}\left[\bar{c} - \frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c}-(A-\delta)\hat{k}\right)\right]\left[\bar{c} + \frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c}-(A-\delta)\hat{k}\right)\right]\\ &+ \gamma\frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c}-(A-\delta)\hat{k}\right)\left[(A-\delta) - \bar{c} + \frac{2(A-\delta)-\rho}{A-\delta}\left(\bar{c}-(A-\delta)\hat{k}\right)\right]\end{aligned} \tag{A.26}$$

which is independent of c_0 and T.

Instead, c_0 and T determine the value of the Hamiltonian at the end of the industrialization phase. Denoting by $c_{T^-} \equiv \lim_{t\to T^-} c_t$ the level of consumption right before date T, the corresponding value of the Hamiltonian is:

$$H^i\left(T, c_0\right) = \frac{\gamma}{2}c_{T^-}\left(2\bar{c} - c_{T^-}\right) - \theta\hat{k} + \lambda_{T^-}\left[(A-\delta)\,\hat{k} - c_{T^-}\right]$$

which, using (A.2) for λ_{T^-}, can be written as:

$$\begin{aligned}H^i\left(T, c_0\right) &= \frac{\gamma}{2}c_{T^-}\left(2\bar{c} - c_{T^-}\right) - \theta\hat{k} + \gamma\left(\bar{c} - c_{T^-}\right)\left[(A-\delta)\,\hat{k} - c_{T^-}\right]\\ &= \gamma\left[\frac{c^2_{T^-}}{2} - \frac{\theta}{\gamma}\hat{k} + (A-\delta)\,\hat{k}\left(\bar{c} - c_{T^-}\right)\right]\end{aligned} \tag{A.27}$$

From (A.5), the consumption just before date T is:

$$c_{T^-} = \bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right)e^{-(A-\delta-\rho)T} \tag{A.28}$$

It follows that that:

$$\begin{aligned}\frac{\partial G}{\partial c_0} &= \frac{\partial H^i}{\partial c_0} = -\gamma\left((A-\delta)\,\hat{k} - c_{T^-}\right)\frac{\partial c_{T^-}}{\partial c_0}\\ &= -\gamma\left((A-\delta)\,\hat{k} - c_{T^-}\right)e^{-(A-\delta-\rho)T} < 0\end{aligned}$$

The sign is established by noticing that the term in brackets on the second line is net investment in capital $\dot{k}_{T^-}$ just before date T, which is positive along an accumulation path, i.e. reaching $\hat{k}$ from below. Moreover:

$$\begin{aligned}\frac{\partial G}{\partial T} &= \frac{\partial H^i}{\partial T} = -\gamma\left((A-\delta)\,\hat{k} - c_{T^-}\right)\frac{\partial c_{T^-}}{\partial T}\\ &= -\gamma\left((A-\delta)\,\hat{k} - c_{T^-}\right)(A-\delta-\rho)\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right)e^{-(A-\delta-\rho)T} < 0\end{aligned}$$

The sign is determined by two facts: (*i*) capital accumulation enables reaching $\hat{k}$ from below, so that $\dot{k} > 0$ for all $t \leq T$, and in particular at $t = T$; (*ii*) the optimal initial level of consumption is lower than the level of consumption that would be attained asymptotically under myopic regulation, as argued above.

We conclude that along the optimal development path encompassing structural change, the *junction condition* implies a negative relationship between the two endogenous variables c_0 and T:

$$\left.\frac{dc_0}{dT}\right|_{G=0} = -\frac{\partial G/\partial T}{\partial G/\partial c_0} = -(A-\delta-\rho)\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - c_0\right) < 0 \tag{A.29}$$

Existence and uniqueness. The candidate optimal solution implies a unique couple of values $\left(T^*, c_0^*\right)$, defined as the point where the $F = 0$ and $G = 0$ loci, characterized by (A.14) and (A.15), cross in the (T, c_0) space.

Since according to (A.25) and (A.29) the schedule $\left.c_0(T)\right|_{G=0}$ decreases while the schedule $\left.c_0(T)\right|_{F=0}$ is increasing in T, a unique solution exists if and only if the former is above the latter at $T = 0$, i.e. if $\left.c_0(0)\right|_{G=0} > \left.c_0(0)\right|_{F=0}$, and below it for at least one $T > 0$.

Condition $F = 0$ requires that $k_T = \hat{k}$. Hence, for $T = 0$, this implies an instantaneous accumulation such that $\dot{k}_0 = \hat{k} - k_0 \Leftrightarrow (A-\delta)\,k_0 - c_0 = \hat{k} - k_0$ from (2.2), i.e.:

$$\left.c_0(0)\right|_{F=0} = (A-\delta)\,k_0 - \left(\hat{k} - k_0\right) \tag{A.30}$$

In condition $G = 0$, variables T and c_0 exert their effect through c_{T^-}. Notice that $T = 0 \Rightarrow c_{T^-} = c_0$ in (A.28). Therefore, the variable term H^i in (A.27) depends directly on c_0, and condition $G = 0$ yields:

$$\frac{\gamma}{2}c_0^2 - \theta\hat{k} + \gamma\,(A-\delta)\,\hat{k}\left(\bar{c} - c_0\right) = \hat{H}$$

where $\hat{H}$ is a constant given in (A.26). Assuming $1 - \frac{2}{\hat{k}}\left(\frac{\bar{c}}{A-\delta} - \frac{\hat{H}/\hat{k}+\theta}{\gamma(A-\delta)^2}\right) > 0$, the relevant solution is:

$$\left.c_0(0)\right|_{G=0} = (A-\delta)\,\hat{k} - \sqrt{\frac{2}{\gamma}\left(\hat{H} + \theta\hat{k}\right) + (A-\delta)\,\hat{k}\left[(A-\delta)\,\hat{k} - 2\bar{c}\right]} \tag{A.31}$$

where the negative sign is selected in front of the second term on the right-hand side, since $c_0 < \hat{c} \Rightarrow (A-\delta)\,\hat{k} - c_0 > (A-\delta)\,\hat{k} - \hat{c} > 0$, making inadmissible the case with a positive sign.

Hence, for the solution to exist (A.31) should be larger than (A.30), i.e.:

$$(A-\delta)\,\hat{k} - \sqrt{\frac{2}{\gamma}\left(\hat{H} + \theta\hat{k}\right) + (A-\delta)\,\hat{k}\left[(A-\delta)\,\hat{k} - 2\bar{c}\right]} > (A-\delta)\,k_0 - \left(\hat{k} - k_0\right)$$

implying condition (3.10) with:

$$\Omega \equiv \left[1 - \frac{A-\delta}{1+A-\delta}\sqrt{1 - \frac{2}{\hat{k}}\left(\frac{\bar{c}}{A-\delta} - \frac{\hat{H} + \theta\hat{k}}{\gamma\,(A-\delta)^2\,\hat{k}}\right)}\,\right] \tag{A.32}$$

Finally, we can check that there exists a $\check{T} > 0$ such that $G = 0$ for $c_0 = 0$. Setting $c_0 = 0$ in (A.28), substituting the result into (A.27), the junction condition (A.15) is

$$\frac{\gamma}{2}\left(1 - e^{-(A-\delta-\rho)\check{T}}\right)^2\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right)^2 - \theta\hat{k}$$
$$+\gamma\,(A-\delta)\,\hat{k}\left(\bar{c} - \left(1 - e^{-(A-\delta-\rho)\check{T}}\right)\left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho}\right)\right) - \hat{H} = 0$$

where $\hat{H}$ is given in (A.26). This expression admits a unique positive root $\check{T} > 0$, which is the coordinate of the point where function $\left.c_0(T)\right|_{G=0}$ crosses the horizontal axes.[27] The junction condition at date $\check{T}$ can be rewritten as:

$$c_\infty^m\left(1 - e^{-(A-\delta-\rho)\check{T}}\right) = \frac{\hat{H} - \gamma(A-\delta)\bar{c}\hat{k} + \theta\hat{k}}{\frac{\gamma}{2}c_\infty^m(1 - e^{-(A-\delta-\rho)\check{T}}) - \gamma(A-\delta)\hat{k}} \tag{A.33}$$

Using (A.20)–(A.23), (3.3) and (3.4), the target condition can be written as

$$\begin{aligned} c_\infty^m\left(1 - e^{-(A-\delta-\rho)T}\right) &= c_\infty^m\left(1 - e^{(A-\delta)T}\right) + c_0 e^{(A-\delta)T}\left(1 - e^{-(2(A-\delta)-\rho)T}\right) \\ &\quad + (2(A-\delta)-\rho)(\hat{k} - k_\infty^m + (k_\infty^m - k_0)e^{(A-\delta)T}) \end{aligned} \tag{A.34}$$

Substituting the right-hand side of (A.33) for the left-hand-side in (A.34), the target condition at date $\check{T}$ implies

$$c_0 = \frac{1 - e^{-(A-\delta)\check{T}}}{1 - e^{-(2(A-\delta)-\rho)\check{T}}}c_\infty^m + \frac{e^{-(A-\delta)\check{T}}}{1 - e^{-(2(A-\delta)-\rho)\check{T}}}\Bigg[-(2(A-\delta)-\rho)(\hat{k} - k_\infty^m + (k_\infty^m - k_0)e^{(A-\delta)\check{T}}) \tag{A.35}$$

[27] At first glance, one may want to complete the demonstration by finding the conditions warranting that $\lim_{T\to\infty} \left.c_0(T)\right|_{G=0} < \lim_{T\to\infty} \left.c_0(T)\right|_{F=0}$. However, as $T \to \infty$ the term c_{T^-} in $G = 0$ is independent of c_0, so that $G = 0$ does not hold at the limit ($\lim_{T\to\infty} c_{T^-} = c_\infty^m$). Similarly $F = 0$ does not hold for $T \to \infty$: either factor $e^{(A-\delta)T}$ diverges, or c_0 is set to keep this factor null, which would require that $\lim_{T\to\infty} k_T = k_\infty^m < \hat{k}$, thus $F \neq 0$.

$$+\frac{\hat{H}-\gamma(A-\delta)\bar{c}\hat{k}+\theta\hat{k}}{\frac{\gamma}{2}c^m_\infty(1-e^{-(A-\delta-\rho)\check{T}})-\gamma(A-\delta)\hat{k}}\Bigg]$$

which is required to be positive, completing the proof for the existence of a unique solution (c_0^*, T^*) with $c_0^* \in \left(c_0(0)|_{F=0}, c_0(0)|_{G=0}\right)$, defined in (A.30)–(A.31), and $T^* \in \left(0, \check{T}\right)$. □

Welfare (A.36) is obtained using (A.18)–(A.19) in $(\mathcal{P}^*)$. Using definition (A.14) with (3.5) and (3.6) and $\theta = 0$ to compute W^s, (3.3) and (3.4), welfare can be expressed as

$$\begin{aligned} W^* = {} & e^{-\rho T^*} W^s\left(\hat{k}\right) + \frac{1}{\rho}\left(1-e^{-\rho T^*}\right)\left(\gamma c^i_\infty\left(\bar{c}-\frac{c^i_\infty}{2}\right)-\theta k^i_\infty\right) \\ & -\frac{1}{A-\delta}\left(1-e^{-(A-\delta)T^*}\right)\left[\gamma\left(\bar{c}-c^i_\infty\right)-\frac{\theta}{2(A-\delta)-\rho}\right]\left(c^i_\infty-c^*_0\right) \\ & \frac{1}{2(A-\delta)-\rho}\left(1-e^{-(2(A-\delta)-\rho)T^*}\right)\frac{\gamma}{2}\left(c^i_\infty-c^*_0\right)^2 \\ & \frac{1}{A-\delta-\rho}\left(e^{(A-\delta-\rho)T^*}-1\right)\theta\left(k_0-k^i_\infty+\frac{c^i_\infty-c^*_0}{2(A-\delta)-\rho}\right) \end{aligned} \tag{A.36}$$

A.3. Calibration

Following Hassler and Krusell (2018) we set the depreciation rate at 7%. We calibrate the parameter of capital productivity, A, to obtain an asymptotic saving rate at 21% in the service economy, close to the average gross savings rate in high income countries over the last 25 years.[28] The results hereafter in Section 5 suggest $\hat{y} = 38{,}000$ 2010 US dollars, which implies $\hat{k} = 114{,}000$ 2010 US dollars given A. The emissions intensity of fossil resource use ζ depends on the mix of fossil resources used. We select its value to match the CO_2 intensity of energy use (2.62 kg CO_2/kg of oil equivalent) and the share of fossil fuels in energy consumption (78%) for low and medium income countries averaged over the period 1995–2014.[29] The productivity of fossil energy in the production function during the industrial phase, b, is chosen so that the average CO_2 intensity of GDP is 1.122 tCO_2/\$ as in the first three income deciles in our sample.[30]

For the preference parameters, let us use the rate of preference for the present at 1% as in Hassler and Krusell (2018). Parameter γ is chosen in order to normalize the asymptotic utility level under structural change at $\tilde{u} = 100$.[31] To set the value of the preference parameter measuring the marginal disutility of polluting emissions, $\tilde{\theta}$, first notice that it affects the distance between the asymptotic levels of consumption in (3.4) and (3.6). More precisely these two equations and the definition of $\theta \equiv \tilde{\theta}\zeta A/b$ imply $(\bar{c} - c^m_\infty)/\bar{c} = (\tilde{\theta}/\gamma)\zeta A/[(A-\delta-\rho)b\bar{c}]$. This expression is used to pin down the value of $\tilde{\theta}$, by specifying a value for its left-hand side. This is done using estimates of the loss of consumption in the long-run, resulting from climate change mitigation policies, relative to business-as-usual scenarios. In our framework the latter implies capital accumulation chosen without taking into account the impact of pollution on households, which leads to asymptotic consumption c^b_∞ in (3.6). Instead, the asymptotic consumption under a strict environmental policy, not taking into account the benefit of structural change, is given by (3.4) but with a strictly positive θ.[32] Assuming a value $\bar{c} = 31$ (implying $\bar{y} = 39{,}240$ 2010 US dollars), we calibrate the value of $\tilde{\theta}$ on a reduction of approximately 4% in asymptotic consumption. Such a loss is equivalent to the welfare loss for China by 2050 in the scenario with a strict international carbon policy obtained by Bretschger and Zhang (2017) using their endogenous growth model.[33]

A.4. Resolution of the program in Section 4

The problem from date T onward is identical to that examined in Section 3.2 and Appendix A.1 with $\hat{k}$ and $t-T$ substituting for k_0 and t respectively, and moreover with the pollution stock declining at constant rate α. The Lagrangian of problem up to date $\hat{T}$(4.4) implies the following first order conditions:

$$\gamma(\bar{c}-c_t) = \lambda_t \qquad \Leftrightarrow \qquad c_t = \bar{c} - \frac{\lambda_t}{\gamma} \tag{A.37}$$

---

[28] In the service economy, at steady state the gross investment rate is $\left(\dot{k}^b_\infty + \delta k^b_\infty\right)/Ak^b_\infty = 1 - c^b_\infty/(Ak^b_\infty) = \delta/A$, using (2.2) and (3.5). Data retrieved from the WDI portal at the World Bank.

[29] Denoting total energy use N, its emissions intensity $ei \equiv e/N$ and the share of fossil fuel is $fs \equiv f/N$, the definition of the parameter $\zeta \equiv e/f$ is directly used $\zeta = ei/sf$. Data retrieved from the WDI portal at the World Bank.

[30] Combining $b = k/f$ and $k = y/A$, from the production function (2.1), with $f = e/\zeta$ from the definition of ζ, one obtains $b = (\zeta/A)/(e/y)$.

[31] Under structural change the asymptotic utility level is $\tilde{u}_\infty = \gamma\bar{c}^2/2$.

[32] To the extent that in our model the only form of technological progress is offered by structural change, to be coherent with our approach we should use estimates of the cost of climate mitigation policies based on models without any technological progress. However, we prefer to rely on estimates provided by more general models encompassing endogenous technological change.

[33] Other values could be used to calibrate the preference ratio $\tilde{\theta}$, from applied models of climate change that evaluate the cost of climate change mitigation in terms of foregone income with respect to a business-as-usual scenario. Chen et al. (2016), for instance, run the EPPA 6 model for a trajectory over which global CO_2 emissions decline 50% by 2050 and 80% by 2075 from their level in 2010, and find a loss in GDP of 8.3% by 2050. We could also use the most recent versions of the DICE model by Nordhaus (1992), which quantify the impact of climate policies in terms of reduction in consumption with respect to business-as-usual scenarios. This loss is partially compensated by avoided losses in total factor productivity in the DICE model, as well as in most integrated assessment models used in the assessment of climate policies (Tol, 2009, 2014).

$$\dot{\lambda}_t = \theta + \beta\mu_t - (A-\delta-\rho)\lambda_t \tag{A.38}$$

$$\dot{\mu}_t = (\rho-\alpha)\mu_t + \nu \tag{A.39}$$

and the complementarity slackness condition:

$$\nu \geq 0,\ \bar{S} - S_t \geq 0,\ \nu\left(\overline{S} - S_t\right) = 0$$

There may exist two phases up to date T: during the first phase pollution is below the ceiling, during the second one is at the ceiling. When pollution is at the ceiling, it can either stay there or fall below it immediately. For pollution to stay at the ceiling we have that $\dot{S} = 0$ requires $k_t = \alpha\bar{S}/\beta$ be constant, so that T cannot be attained. We deduce that the ceiling may only become binding at date T. Therefore $\nu = 0$ for all $t < T$ and $t > T$, $\nu > 0$ at $t = T$.

Taking this result into account, the differential equation for μ, $\dot{\mu}_t = (\rho-\alpha)\mu_t$ can be integrated:

$$\mu_t = \mu_0 e^{-(\alpha-\rho)t}$$

As we have $\mu_0 \geq 0$ since $\mu_t \geq 0$ by definition, μ is decreasing (increasing) for $\alpha > \rho$ ($\alpha < \rho$).

To integrate (A.38) we define $z_t \equiv \lambda_t e^{(A-\delta-\rho)t}$ and apply the procedure in footnote 26 , to obtain λ_t as function of μ_0 and the constant of integration $\bar{z}$. The value of the latter is pinned down using (A.37) at date t=0, allowing us to write λ_t and c_t as a function of c_0 and μ_0:

$$\lambda_t = \frac{\theta}{A-\delta-\rho}\left(1-e^{-(A-\delta-\rho)t}\right) + \gamma(\bar{c}-c_0)e^{-(A-\delta-\rho)t} + \frac{\beta\mu_0}{A-\delta-\alpha}e^{-(\alpha-\rho)t}\left(1-e^{-(A-\delta-\alpha)t}\right)$$

$$c_t = c_0 e^{-(A-\delta-\rho)t} + \left(\bar{c} - \frac{\theta/\gamma}{A-\delta-\rho} - \frac{\beta\mu_0/\gamma}{A-\delta-\alpha}\right)\left(1-e^{-(A-\delta-\rho)t}\right) + \frac{\beta\mu_0/\gamma}{A-\delta-\alpha}\left(1-e^{-(\alpha-\rho)t}\right) \tag{A.40}$$

To express the trajectory of capital as a function of c_0, we apply the integration procedure in Appendix A.1 to $\omega_t \equiv e^{-(A-\delta)t}k_t$, use the initial condition on k_0 to pin down $\bar{\omega}$, the definitions (3.3), (3.4) and $m \equiv \frac{\beta\mu_0/\gamma}{A-\delta-\alpha}$, to write:

$$\begin{aligned} k_t \;=\; & k_\infty^m - \left(c_\infty^m - c_0\right)\frac{e^{-(A-\delta-\rho)t}}{2(A-\delta)-\rho} \\ & + \frac{e^{(A-\delta)t}}{2(A-\delta)-\rho}\left[\left(c_\infty^m - c_0\right) - \left(k_\infty^m - k_0\right)(2(A-\delta)-\rho)\right] \\ & + m\left[e^{(A-\delta)t}\left(\frac{A-\delta-\alpha}{(A-\delta-\rho+\alpha)(2(A-\delta)-\rho)}\right) + \frac{e^{-(A-\delta-\rho)t}}{2(A-\delta)-\rho} - \frac{\left(e^{-(\alpha-\rho)t}\right)}{A-\delta-\rho+\alpha}\right] \end{aligned} \tag{A.41}$$

The path of the pollution stock is obtained by defining $\chi_t \equiv e^{\alpha t}S_t$, using the law of motion (4.3) to get $\dot{\chi}_t = e^{\alpha t}\beta k_t$, substituting for k_t using (A.41), then integration following the usual procedure, and finally substituting the constant of integration using the initial condition S_0. This gives:

$$\begin{aligned} S_t^\diamond \;=\; & S_0 e^{-\alpha t} + \frac{1}{\alpha}\beta k_\infty^m\left(1-e^{-\alpha t}\right) + \frac{1}{-(A-\delta-\rho)+\alpha}\beta\left(c_\infty^m - c_0^\diamond\right)e^{-\alpha t}\frac{\left(1-e^{-(A-\delta-\rho-\alpha)t}\right)}{2(A-\delta)-\rho} \\ & + \frac{\beta}{A-\delta+\alpha}\frac{e^{-\alpha t}\left(e^{(A-\delta+\alpha)t}-1\right)}{2(A-\delta)-\rho}\left[\left(c_\infty^m - c_0^\diamond\right) - \left(k_\infty^m - k_0\right)(2(A-\delta)-\rho)\right] \\ & + \frac{\beta^2\mu_0^\diamond/\gamma}{A-\delta-\alpha}\left[\frac{\left(e^{(A-\delta)t}-e^{-\alpha t}\right)}{A-\delta+\alpha}\left(\frac{A-\delta-\alpha}{(A-\delta-\rho+\alpha)(2(A-\delta)-\rho)}\right) - \frac{1}{(A-\delta-\rho-\alpha)}\frac{\left(e^{-(A-\delta-\rho)t}-e^{-\alpha t}\right)}{2(A-\delta)-\rho} - \frac{1}{\rho}\frac{\left(e^{-(\alpha-\rho)t}-e^{-\alpha t}\right)}{A-\delta-\rho+\alpha}\right] \end{aligned} \tag{A.42}$$

Using (A.40) and (A.41) for $c_t^\diamond$ and $k_t^\diamond$, we can get an explicit expression for welfare as a function of $c_0^\diamond$, $T^\diamond$ and $\mu_0^\diamond$ as follows:

$$\begin{aligned} W^\diamond = \;& e^{-\rho T^\diamond}W^b + \gamma\bar{c}c_\infty^m T^\diamond + \left(\frac{\gamma}{2\rho}(c_\infty^m)^2 + \frac{\theta k_\infty^m}{\rho}\right)(1-e^{-\rho T^\diamond}) - \frac{\gamma m^2}{2(2\alpha-\rho)}(1-e^{-(2\alpha-\rho)T^\diamond}) \\ & + \frac{\theta\left(c_0^\diamond - c_\infty^m + m\right)}{(A-\delta-\rho)[2(A-\delta)-\rho]}(1-e^{-(A-\delta)T^\diamond}) + \frac{\gamma m(c_0^\diamond - c_\infty^m + m)}{A-\delta-\rho-\alpha}(1-e^{-(A-\delta-\rho-\alpha)T^\diamond}) \\ & - \frac{c_\infty^m - c_0^\diamond - (k_\infty^m - k_0)[2(A-\delta)-\rho] + \frac{A-\delta-\alpha}{A-\delta-\rho\alpha}}{(A-\delta-\rho)[2(A-\delta)-\rho]}\theta(1-e^{-(A-\delta-\rho)T^\diamond}) - \frac{\gamma\bar{c}m}{\alpha-\rho}(1-e^{-(\alpha-\rho)T^\diamond}) \\ & - \frac{\gamma(c_0^\diamond - c_\infty^m + m)^2}{2[2(A-\delta)-\rho]}(1-e^{-[2(A-\delta)-\rho]T^\diamond}) + \frac{m}{\alpha}\left(\frac{\gamma c_\infty^m}{2} + \frac{\theta}{A-\delta-\rho-\alpha}\right)(1-e^{-\alpha T^\diamond}) \end{aligned} \tag{A.43}$$

Finally, we compute the pollution stock resulting from the policy characterized in Proposition 3, which is useful to express the threshold $\tilde{S}_0$ on the initial pollution stock defined in (4.5) and to compare the optimal paths encompassing structural change with and without a binding ceiling on the pollution stock. First, we express (A.7) using definitions (3.3) and (3.4). Second we use the initial condition to substitute for $\bar{x}$, to get k_t as a function of t, c_0 and parameterized by c_∞^m and k_∞^m. Third, proceeding as above, we obtain the following expression of the pollution stock along the optimal trajectory with structural change without a binding pollution ceiling:

$$S_t^* = e^{-\alpha t} S_0 + \frac{\beta}{\alpha} k_\infty^m \left(1-e^{-\alpha t}\right) - \beta\left(k_\infty^m - k_0 - \frac{c_\infty^m - c_0^*}{2(A-\delta)-\rho}\right)\frac{e^{(A-\delta)t}-e^{-\alpha t}}{A-\delta+\alpha} + \frac{\beta\left(c_\infty^m - c_0^*\right)}{2(A-\delta)-\rho}\frac{e^{-(A-\delta-\rho)t}-e^{-\alpha t}}{A-\delta-\rho-\alpha}$$

A.5. Descriptive statistics

Table 4
Unbalanced data set descriptive statistics.

	CO_2/CAP	GDP/CAP	VA SERV	VA INDUS	POP	POP < 14	POP 15–64	IMPORT
Obs.	8,998	8,751	6,205	7,415	11,125	10,937	10,937	8,274
Mean	9.23	11 044	50.40	26.97	1,35E+07	34.64	59.02	42.64
Std. Dev.	19.55	16 463	13.49	13.63	5,19E+07	10.43	7.02	29.44
Min	0.01	116	4.79	1.88	1,64E+04	11.06	45.27	0.00
Max	262.75	144 246	155.55	213.69	6,72E+08	51.89	85.87	427.58
CO_2/CAP	1.000							
GDP/CAP	0.7153	1						
VA SERV	0.2574	0.4448	1					
VA INDUS	0.2703	0.0198	−0.4615	1				
POP	−0.2009	−0.217	−0.1963	−0.0212	1			
POP<14	−0.5904	−0.5081	−0.425	−0.1238	0.1968	1		
POP 15–64	0.6063	0.5009	0.4184	0.17	−0.1848	−0.9656	1	
IMPORT	0.3937	0.3318	0.3032	0.0059	−0.2982	−0.3412	0.3579	1

List of countries in the unbalanced panel

Afghanistan, Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Armenia, Australia, Austria, Azerbaijan, The Bahamas, Bahrain, Bangladesh, Barbados, Belarus, Belgium, Belize, Benin, Bhutan, Bolivia, Bosnia and Herzegovina, Brazil, Brunei Darussalam, Bulgaria, Burkina Faso, Cabo Verde, Cambodia, Cameroon, Canada, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo Dem. Rep., Congo Rep., Costa Rica, Cote d'Ivoire, Croatia, Cyprus, Czech Republic, Denmark, Dominican Republic, Ecuador, El Salvador, Equatorial Guinea, Estonia, Ethiopia, Fiji, Finland, France, Gambia, Georgia, Germany, Ghana, Greece, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hong Kong SAR, China, Hungary,Iceland, India, Indonesia, Iran, Islamic Rep., Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Kiribati, Korea Rep., Kuwait, Kyrgyz Republic, Lao PDR, Latvia, Lebanon, Lesotho, Liberia, Lithuania,Luxembourg, Macao SAR, China, Macedonia, FYR, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Moldova, Montenegro, Morocco, Mozambique, Namibia, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russian Federation, Rwanda, Saudi Arabia, Serbia, Seychelles, Sierra Leone, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Sweden, Switzerland, Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Turkey, Turkmenistan, Uganda, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Uzbekistan, Venezuela, Vietnam, West Bank and Gaza, Rep. of Yemen, Zambia, Zimbabwe.

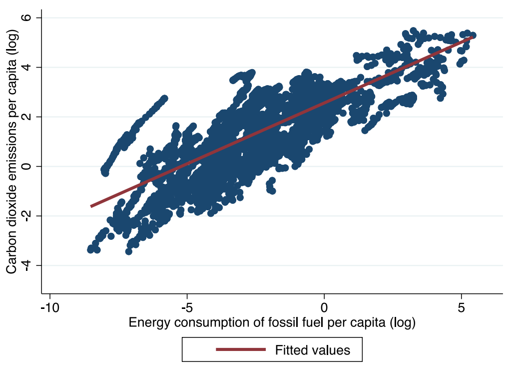

Fig. 4. Scatter plot of CO_2 per capita and energy for fossil fuels for the entire sample 1960–2014.

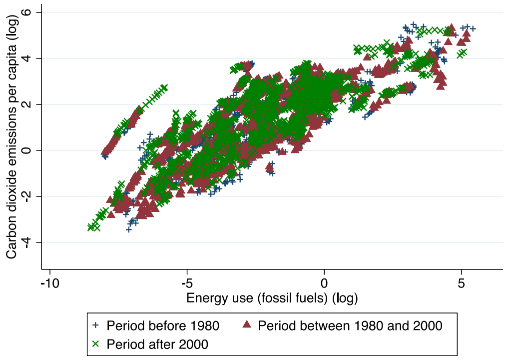

Fig. 5. Scatter plot of CO_2 per capita and energy for fossil fuels for the entire sample 1960–2014.

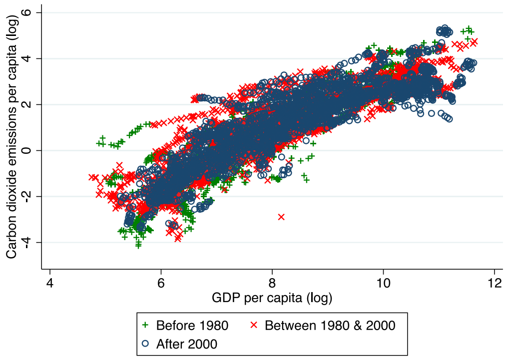

Fig. 6. Scatter plot over time of CO_2 per capita and energy for fossil fuels for the entire sample 1960–2014.

A.6. Empirical results

Table 5
Results for FE, FE non-linear and FGLS estimations.

Variables	FE (1)	FE NL (2)	FGLS (3)
GDP/CAP (log)	0.718***	2.221***	2.189***
	(0.0799)	(0.328)	(0.0929)
Square of GDP/CAP		−0.0949***	−0.0815***
		(0.0195)	(0.00573)
VA SERV (% of GDP)	0.00554**	0.00366*	0.00260***
	(0.00230)	(0.00207)	(0.000602)
VA INDUS (% of GDP)	0.0100***	0.00879***	0.00694***
	(0.00317)	(0.00303)	(0.000667)
POP (log)	0.318***	0.271***	0.0601***
	(0.0953)	(0.0935)	(0.00806)
POP<14	0.0588***	0.0250	0.0118**
	(0.0183)	(0.0180)	(0.00501)
POP 15–64	0.0612***	0.0285	0.0502***
	(0.0203)	(0.0198)	(0.00615)
IMPORT	0.00209**	0.00217**	0.00144***
	(0.00100)	(0.000943)	(0.000169)
Constant	−15.98***	−17.79***	−16.01***
	(2.544)	(2.503)	(0.658)
Observations	5,095	5,095	2,310
R-squared	0.484	0.509	
Number of country_codes	157	157	70

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 6
Impact of income on CO_2 - Results of dynamic panel regressions.

Dep. variable $\ln CO_2/CAP$	One step	Two steps		
	(1)	(2)	(3)	(4)
Variables				
Lag 1 CO_2/CAP	0.669***	0.663***	0.497***	0.704***
	(0.0160)	(0.00481)	(0.00172)	(0.00197)
Lag 2 CO_2/CAP	0.0131	0.0144***	−0.00692***	0.0148**
	(0.0165)	(0.00422)	(0.000885)	(0.00620)
Lag 3 CO_2/CAP	0.0491***	0.0540***	0.0362***	0.0466***
	(0.0126)	(0.00510)	(0.000646)	(0.00347)
GDP/CAP (log)	0.899***	0.925***	1.420***	0.787***
	(0.0920)	(0.0267)	(0.0167)	(0.0567)
Square of GDP/CAP	−0.0432***	−0.0442***	−0.0667***	−0.0381***
	(0.00562)	(0.00161)	(0.00101)	(0.00311)
VA SERV (% of GDP)	−0.000574	−0.000453***	−8.41e−05	−0.000349***
	(0.000557)	(0.000108)	(5.56e−05)	(0.000125)
VA INDUS (% of GDP)	0.00212***	0.00214***	0.00296***	0.00211***
	(0.000683)	(0.000154)	(8.02e−05)	(0.000142)
POP (log)	0.0411**	0.0299***	0.191***	0.0600***
	(0.0170)	(0.0106)	(0.0108)	(0.00674)
POP <14	0.0105**	0.0116***	0.0243***	0.00406***
	(0.00501)	(0.00165)	(0.00126)	(0.00117)
POP 15–64	0.0112**	0.0120***	0.0193***	0.00445***
	(0.00541)	(0.00173)	(0.00142)	(0.00118)
IMPORT	0.000882***	0.000797***	0.000586***	0.000487***
	(0.000278)	(4.98e−05)	(2.36e−05)	(2.65e−05)
Constant	−5.802***	−5.859***	−11.48***	−4.936***
	(0.583)	(0.252)	(0.221)	(0.281)
Observations	4,803	4,803	4,803	4,803
Number of country_codes	156	156	156	156
Number of instruments	1400	1400	256	3000
AR2 test *p*-value		0.7476	0.6779	0.6920

A.7. Dynamic model

This approach is usually considered by referring to the work of Arellano and Bond (Arellano and Bond, 1991). A dynamic model enables addressing individual effects and numerous periods simultaneously, and in turn, the endogeneity of the model or independent regressors. Moreover, relying on a Generalized Method of Moments (GMM) approach, we may obtain more efficient estimates from the dynamic panel data model to deal with the Nickell bias. The Arellano–Bond estimator sets up a GMM problem in which the model is specified as a system of equations, one per time period, where the instruments applicable to each equation differ (for instance, in later time periods, additional lagged values of the instruments are available). The model estimated is the following:

$$\ln e_{it} = \boldsymbol{\eta}_1''' \mathcal{E}_{i,lag} + \eta_2''' \ln \tilde{y}_{it} + \eta_3'''(\ln \tilde{y}_{it})^2 + \eta_4''' V_{it} + \eta_5''' X_{it} + v_{i0}''' + \epsilon_{it}''' \tag{A.44}$$

where $\mathcal{E}_{i,lag}$ denotes the vector of lagged values of the log of CO_2/CAP, $\boldsymbol{\eta}_1'''$ the vector of associated autoregressive parameters, $\tilde{y}$ the instrumented variable for GDP per capita, and v_{i0}''' denotes a full set of country fixed effects, capturing the impact of any time-invariant country characteristics.

Two different estimators can be obtained: (*i*) the 2SLS estimator also called the one-step estimator (*ii*) the more efficient optimal GMM estimator, also called the two-step estimator because a first-step estimation is needed to obtain the optimal weighting matrix used in the second step. Results are presented in Table 6. Our GMM estimations use three lags of the dependent variable as instruments.[34] In column (1), results are presented for the one step estimator. In column (2), (3) and (4) results are presented for the two-step estimator. In regression (3) compared with (2), we reduce the number of instruments. To avoid bias, we chose models that reduce the number of instruments at the (potential) expense of efficiency.[35] In column (4) we consider potential endogeneity due to simultaneity between the dependent variable and income per capita. Thus, income per capita is also instrumented with lags,

[34] The AR2 row reports the *p*-value for a test of serial correlation in the residuals of the CO_2 emissions per capita series.

[35] An issue in GMM estimation is choosing the right number of moment conditions. Indeed, there is evidence that using too many instruments introduces bias while increasing efficiency (Baltagi, 2008). The number of available potential instruments increases with the number of periods. We have to choose the number of lags of the dependent variable to be used as instruments, in order to take advantage of the trade-off between the reduction in the bias and the loss in efficiency.

a procedure that increases the number of instruments but corrects the estimates from potential endogeneity. Therefore, we favor estimates of the model in column (4) of Table 6.

All the estimated coefficients are significant and have the expected signs. The coefficient of GDP is positive and equal to 0.787. The value of the coefficient of the square of GDP is negative and significant which demonstrates, once again, the presence of a non-linearity between carbon dioxide emissions and income per capita. The value of the threshold is equal to 30,576 US dollars per capita.[36] This threshold is less than the one we obtained with the PTR. This is not surprising since low-income countries are considered here (we have an unbalanced panel data set).

Our empirical exercises validate the hypothesis of a reduction in the role of fossil energy in growth as the economy develops, hence providing some justification for the assumption of structural change in the theoretical model.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2024.102981.

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[36] In fact, $(-\eta_2'''/(2\eta_3''')) = 10.328$ and $\hat{y} = e^{10.328} = 30{,}576$ 2010 US dollars.