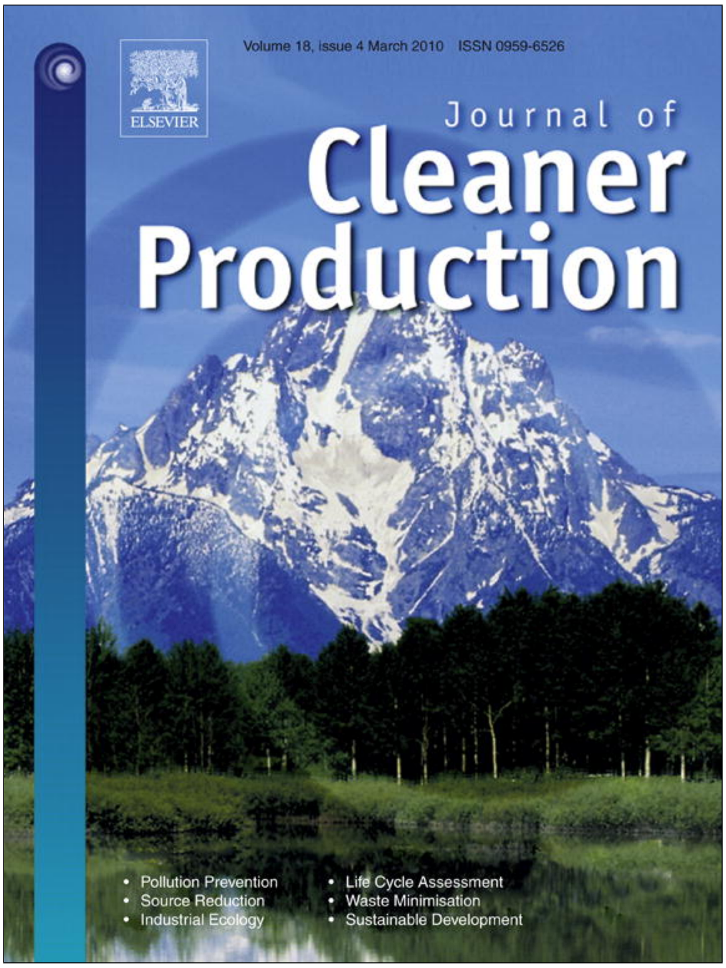
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# Energy transition towards economic and environmental sustainability: feasible paths and policy implications

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A B S T R A C T

This paper focuses on growth feasibility in an era of increasing scarcity of fossil fuels. A stylised dynamic model illustrates the implications of investing in smooth technological progress in the field of renewable energy. Positive rates of GDP growth sustained by fossil fuels entail, on the one hand, more income available for R&D in renewable energy sources, and on the other, an acceleration of the exhaustible resource depletion time. Our model explores such a trade-off and highlights the danger of high growth rates. Policies should target low growth rates, stimulate investment in alternative energy sources and discourage consumption growth.



## 1. Introduction

The present paper focuses on the relationship between GDP growth and the increasing scarcity of energy availability, with special emphasis on the possibility that exhaustible energy sources may 'run out' before sufficient knowledge and production capacity in alternative (and cleaner) sources has been developed. Therefore, it tackles a classic topic in the field of natural resource economics,[1] that is, the study of the conditions under which an economy facing an exhaustible resource constraint will enter onto a sustainable path.

Many economists have an optimistic attitude towards the problem since they believe that resource scarcity, signalled by price increases, will stimulate both technological progress and substitution of natural resources with capital. As Nordhaus and Tobin stated ([8], p. 523),

> [i]f the past is any guide for the future, there seems to be little reason to worry about the exhaustion of resources which the market already treats as economic good.

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[1] The basic theoretical framework of the conventional approach to exhaustible resources started with three seminal papers published in a special issue of the Review of Economic Studies, Dasgupta and Heal [1], Solow [2] and Stiglitz [3]. They developed one-sector models of neoclassical growth with exogenous technical progress where, along with capital and labour, a non-renewable resource also enters the production function. Without technical progress, the optimal path determined in Dasgupta and Heal [1] – maximizing present value optimality – involves a reduction of consumption and utility in the long-run. Solow [2] showed that constant consumption is feasible provided that a composite stock of natural and man-made capital is kept constant. This result has been developed through the formulation of Hartwick's rule, which states that "the investment of current exhaustible resource returns in reproducible capital implies per capita consumption constant" (Hartwick [4], p. 974). In the 90s, endogenous growth theory entered the sustainability debate. Smulders [5], surveying this literature, shows that the general condition for exponential growth to be environmentally sustainable is that the process of accumulation of knowledge – i.e. the engine of economic growth – needs to be fully delinked from physical quantities. If this holds, a "balanced growth path along which economic variables grow at a constant positive rate, but environmental variables remain constant" (Smulders [6], p. 615) will exist. Its feasibility and optimality requires a number of extreme hypotheses (see Bovenberg and Smulders [7]), which, in our view, strongly reduces the policy relevance of the framework.

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Accordingly, the theoretical contributions rule out the possibility of long-run energy shortages "by assuming away the essence of the problem" (Dasgupta and Heal ([1], p. 7)), that is, by postulating the emergence, at an uncertain date in the future, of a "backstop technology" (so named by Nordhaus [9]) consisting in a breakthrough discovery that would substitute for depleting fossil energy and provide the economy with a steady stream of energy resources. Most papers have assumed that the services from the backstop in each period are available without quantitative limits but at a much higher cost than the initial cost of the fossil fuel energy. Others have modelled the backstop as providing an amount of services per period at zero costs. This amount of services can be chosen; in other words it is modelled as a control variable.

The hypothesis of the exogenous emergence of a backstop technology implies a focus on the trend of rents and prices within the optimal depletion path of exhaustible resources. This literature acknowledges that searching for a backstop is a costly process, so that the research agenda "also involves finding the correct allocation of the resources used between the production of goods and expenditure on research" (Dasgupta and Heal ([1], p. 5)). This issue has been explored by assuming that expenditure on R&D affects the date of the backstop discovery (e.g. Dasgupta et al. [10], Kamien and Schwartz [11], Hung and Quyen [12]).

A different line has been followed by Tsur and Zemel [13,14] who consider a smooth technical change process: expenditure on R&D (linearly) increases knowledge accumulation in an already existing technology which, in turn, reduces the cost of the backstop services. At the same time fostering technical progress in renewables subtracts resources from consumption and capital accumulation. Thus, the development of alternative energy sources involves short-run costs (borne for future gains) both in terms of current consumption and growth.

Like Tsur and Zemel, we take into consideration the need for investing in smooth technical change in renewables. The aim of our paper is to explore the consequences of this need in an economy that is characterized by low substitutability between capital and energy and is subject to potential energy shortage.

Following the Occam's razor principle, we develop a dynamic model as simple as possible in order to capture the essence of the problem, that is, to discuss the relationship between economic growth and energy. Such a framework allows us to illustrate the implications of investing in renewable energy sources and to show that the energy transition is a possible, although difficult, task. With the help of some simulations, we compare different policies, involving different paths, and highlight some pros and cons of economic growth. In particular, the paper will show the short- and long-run outcomes of policies that involve different growth rates and time profiles of the energy mix between exhaustible and alternative energy sources.

The paper is structured as follows. Section 2 presents the model. Section 3 discusses the policy implications. Section 4 extends the analysis to take into account the links between economic growth and the natural environment. Section 5 provides some concluding remarks.

## 2. A model

In this section, we first describe the hypotheses of our model, then we deduce its main properties, both in general and under a particular specification. As mentioned above, we attempt to keep the model as simple as possible; thus some assumptions may appear not fully realistic.

### 2.1. The assumptions

Two features characterise our model: the first relates to the production function, the second to technical progress.

The economy produces a composite homogenous good by an AK technology[2] with energy as a complementary input (see equation (1)). We assume complementarity both for theoretical and empirical reasons. Capital is a fund because it participates in many processes and is maintained in efficiency by outside processes. Energy is a flow since it participates in only one production process.[3] Hence, capital and energy should be mainly considered as complementary,[4] involving low elasticity of substitution in the production process. Empirical evidence is controversial since most studies analyze macro data, involving biased estimates of the technical substitution due to aggregation bias (see e.g. Solow [20]). The few studies that use micro data find mixed evidence (Woodland [21], Nguyen and Streitwieser [22], Arnberg and Bjørner [23]). A recent meta-analysis (Koetse, De Groot and Florax [24]) shows that there is some degree of capital/energy substitutability especially in the long-run (but in any case lower than one). It should be noted that the degree of substitutability found in most of the empirical studies is not compatible with the assumptions required by old and new growth theory to meet environmental sustainability.[5] What is uncontroversial is that, since the 1970s, energy efficiency has increased; to take this pattern into account, we introduce an exogenous energy-saving technical progress.

In our model, complementarity between capital and energy is assumed to be perfect since this is the worst case that society could face. Considering some degree of substitutability would complicate the analysis without adding useful insights.

Technical progress, as in Tsur and Zemel [13,14], is acknowledged as a smooth process affected by expenditure on R&D; in contrast to their analysis, however, we model it as a non-linear process that allows for take-off (see equations (6) and (7)). Furthermore, at each time $t$, the amount of harnessed energy is given by past accumulation in alternative energy sources capacity; in other words, we model alternative energy as a state variable. Consequently, in our economy, the reason for investing in the backstop is not a matter of economic returns; rather, it is designed to avoid energy shortages in the future. Positive rates of GDP growth sustained by fossil fuels entail, on the one hand, more income available for investment in the backstop, and on the other, an acceleration of the exhaustible resource depletion time. Our model explores such a trade-off.

The production of the composite commodity $Y$ is

$$Y_t = \min(AK_t, \varepsilon_t E_t) \tag{1}$$

[2] Labour is often not included in growth models. As is well-known, the AK model can be derived (e.g. Barro Sala-I-Martin ([15], p. 144) from a standard neoclassical production function where physical and human capital are perfect substitutable inputs. Hence, capital is taken in a broad sense that includes both physical and human capital. Alternatively, one can assume population as constant (e.g. Hartwick [4]).

[3] Georgescu-Roegen ([16], p. 83–4, 86); cf. Morroni ([17], p. 197–9). Georgescu gave several good examples of the difference between flows and funds. For instance, with a box containing twenty pieces of candy, which are flows, "we can make twenty youngsters happy now or tomorrow, or some today and others tomorrow, and so on." But with one hotel room, which is a fund, "we cannot make one thousand roomless tourists happy now. We can only make one happy today, a second tomorrow, and so on, until the room collapses" (Georgescu-Roegen ([18], p. 226)).

[4] On complementarity between flows and funds, see Georgescu-Roegen ([18], p. 98–9). Cf. Stiglitz's([19], p. 269–70) reply.

[5] If the elasticity of substitution is greater than one, production is possible even without the depletable resource. When elasticity is less than or equal to one non-decreasing utility or even optimal growth is possible only in the presence of a strong enough resource-augmenting technical progress (see Stiglitz [3]). Note that, in endogenous growth models, "the elasticity of substitution between natural capital and the other production factors should equal one" (Bovenberg and Smulders ([7], p. 376)) to make a balanced growth path feasible.

where $K$ is the capital fund, $E$ is the energy flow, $A>0$ is a technological parameter, $\varepsilon$ is energy efficiency. Due to exogenous technical progress $\varepsilon$ is assumed to increase towards a finite limit, $0<\varepsilon_t<\Psi$ $\forall$t, and $\Delta\varepsilon_t/\Delta t>0$.

As usual, capital accumulation is

$$K_{t+1} = I_t^K + \left(1-\delta^K\right)K_t \tag{2}$$

where $I_t^K$ is the level of investment in the capital sector, and $\delta^K$ is the depreciation of capital per unit of time.

We consider two composite energy sources, fossil fuels and alternative energy, and we use the standard, although strong, assumption that the two types of energy are perfect substitutes

$$E_t = Q_t + H_t \tag{3}$$

where $Q$ and $H$ are the services of fossil fuel extraction and alternative energy resource harnessing respectively.

Extraction unit costs, expressed in terms of the resource itself,[6] depend inversely on the exhaustible resource stock, $X_t$. Hence the dynamic of $X$ is

$$X_{t+1} = X_t - Q_t\left(1+\frac{\alpha}{X_t-\alpha}\right) \tag{4}$$

where $\alpha$ is the level of exhaustible resource at which extraction is technically impossible. For the sake of simplicity, we assume that the quantity of fossil fuels, $Q_t$, that can be extracted in each period is unconstrained.

The harnessing of alternative energy sources depends on 'alternative energy source capacity' (henceforth AESC) and is indicated as $R$. For simplicity, we assume that this energy flow is a linear function of $R_t$, that is,

$$H_t = hR_t \tag{5}$$

$R$ increases according to the following accumulation function:

$$R_{t+1} = \left(I_t^R\right)^{\mu} f(R_t) + R_t - \delta^R\left(R_t - R^{\circ}\right) \tag{6}$$

where $I_t^R$ is the level of investment in the alternative resource sector, $\delta^R$ is the depreciation of installed capacity per unit of time, $R^{\circ}$ is a minimum level of AESC which represents the ability of humans to exploit alternative energy sources (such as biomasses) without investing in these sources, and

$$f(R_t) = \beta + \frac{\theta}{1+e^{\eta-\rho R_t}} \quad \text{with } \beta,\theta,\eta,\rho>0 \tag{7}$$

This logistic function takes into account the diffusion of knowledge arising from the increase in the level of $R$. Both the parameter $\mu$ and the function $f(R_t)$ determine the marginal productivity of investment; for $\mu\geq1$ marginal productivity is increasing, for $\mu<1$, marginal productivity can increase for low levels of $R_t$ and is decreasing beyond a certain capacity level. Hence, $\mu<1$ rules out exponential growth in the long-run.

Finally, the economy allocates production between consumption, $C$, and investment, both in broad capital, $I^K$, and in alternative energy capacity, $I^R$, that is,

$$Y_t = C_t + I_t^K + I_t^R \tag{8}$$

[6] Extraction unit costs are usually expressed in terms of the commodity produced by the economy (e.g., Tahvonen and Salo [25]).

## 2.2. Properties of the model

Equation (1) has both a normative and a positive implication. The normative implication is a technical efficiency condition, that is,

$$E_t = AK_t/\varepsilon_t \quad \forall t \tag{9}$$

Hence the supply of energy flows must increase at a rate equal to the rate of capital accumulation less the rate of exogenous technical progress.[7]

The positive implication is that we can distinguish between two polar regimes, depending on whether the binding factor is capital or energy. As long as the exhaustible stock provides a sufficient energy supply, energy is not a limiting factor and alternative energy is not strictly needed. In this case the model is a simple AK growth model (Rebelo [26]) and the economy grows at the rate

$$g^* = (1-c_t)A - \delta^K, \tag{10}$$

where $c_t$ is the propensity to consume and $(1-c_t)$ is the share of income devoted to investment in capital when investment in AESC is zero. In contrast, if energy is the limiting factor, part of the capital is idle and the economy has no incentive in accumulating capital; rather, it has to build AESC.

Before the industrial revolution, the economy was constrained by the energy supply, which was derived from renewable sources. In the era of fossil fuels, the economy has some degree of freedom in choosing the level of investments in AESC. Due to the massive availability of this kind of energy, technical efficiency is obtained by extracting the required amount of fossil fuel. Investment in AESC is costly as it reduces either investments in capital or consumption. For a given level of consumption, a major trade-off shows up: low AESC investments would entail high growth rates, which in turn would increase the availability of resources for investing in AESC itself; at the same time, high growth rates would accelerate extraction of the exhaustible energy sources, leaving less time to prepare the transition (i.e., to accumulate AESC).

A major feature of the model is that the economy can end up either in low or high income and consumption levels, depending on the accumulation paths of AESC and capital. In order to illustrate this property, it is helpful to introduce some specifications. Let us assume that propensity to consume is constant, $c_t=c$ $\forall$t, and that a share of the capital investment, $\phi_t$, is diverted to AESC accumulation. Hence, the allocation of output is

$$Y_t = cY(t) + [1-\phi_t](1-c)Y_t + \phi_t(1-c)Y_t \tag{11}$$

For the sake of the argument, let us consider an economy without fossil energy – that is $Q_t=0$ which implies that available energy is $E_t=hR_t$. Technical efficiency determines the values of $\phi$ that has to be chosen, that is:

$$\phi_t = \begin{cases} \widehat{\phi}, & \text{if } AK_t = \varepsilon_t E_t \\ 1, & \text{if } AK_t > \varepsilon_t E_t \\ 0, & \text{if } AK_t < \varepsilon_t E_t \end{cases} \tag{12}$$

where $\widehat{\phi}$ is such that $g_E=g_K-g_\varepsilon$

The dynamics of the model is driven by two differential equations: the accumulation of capital and the accumulation of AESC. From equations (1) and (2), and (1), (5) and (6), we obtain respectively

[7] More precisely, from equation (9), $\Delta E_t=[\Delta K_t-\Delta\varepsilon_t E_t-\Delta\varepsilon_t\Delta E_t]/\varepsilon_t$ holds. Thus, having defined $g_E=\Delta E_t/E_t$, $g_K=\Delta K_t/E_t$, $g_\varepsilon=\Delta\varepsilon_t/\varepsilon_t$, we have $g_E=g_K-g_\varepsilon-g_\varepsilon g_E$, where $g_\varepsilon g_E\approx0$.

$$\Delta K_t = [(1-\phi_t)(1-c)\min(AK_t, \varepsilon_t hR_t)] - \delta^K K_t \qquad (13)$$

$$\Delta R_t = [\phi_t(1-c)\min(AK_t, \varepsilon_t hR)]^{\mu} f(R_t) - \delta^R (R_t - R^o) \qquad (14)$$

Thus, the isoclines are:

$$\phi_t = 1 - \frac{\delta^K K_t}{(1-c)\min(AK_t, \varepsilon_t hR)} \qquad (15)$$

$$\phi_t = \left[\frac{\delta^R (R_t - R^o)}{f(R_t)}\right]^{1/\mu} \frac{1}{(1-c)\min(AK_t, \varepsilon_t hR)} \qquad (16)$$

If the economy meets the technical efficiency condition, equations (15) and (16) respectively tell us that $\Delta K_t = 0$ if $\phi^* := \phi_t = 1 - \delta^K/[A(1-c)]$ – that is, $\phi$ depends neither on the stock of capital nor on that of AESC – and that the $R$-isocline can be viewed as a relation between $\phi$ and $R$. Thus we can draw Fig. 1 which shows the two isoclines, in the plane $\phi_t$, $R_t$. If $\phi$ is set at the level $\phi^*$, $\Delta K_t = 0$; below that level, capital accumulation is positive, and above it, the stock of capital decreases. The thickest curve is the $R$-isocline: below that curve $R$ decreases, while above it $R$ increases – see the arrows in the graph. The intersections between the two isoclines determine the steady states; we mark the locally stable steady states with a circle. The dashed curve shows, for any level of $R$, the value of $\phi_t$ such that technical efficiency holds.

It is important to note that in the current specification we have ruled out exponential growth by setting parameter $\mu$ (see equation (6)) to a value less than one. As a consequence, the model exhibits two possible steady states without long-term economic growth, a lower one consistent with the minimum level of alternative energy sources, and a higher one that depends on the propensity to save and on the AESC accumulation parameters (see equations (6) and (7)). It is worth emphasizing that Fig. 1 shows only one possible representation of our model. The $R$-isocline (bold curve) could intersect the $K$-isocline ($\phi^*$) only in the low $R$ equilibrium; this occurs when accumulation of AESC requires high amounts of investment and/or the propensity to save is low.

The diagram is also able to depict the relationship between economic growth and energy. Before the industrial revolution, only renewables were used (often unsustainably) and the energy-harnessing capacity of was quite small. Societies were trapped in low-income steady states since the productivity of the investment in AESC was too low to generate an endogenous increase in energy availability. Fossil fuels made energy abundant and fuelled economic growth. If fossil fuels become scarce, the question is whether we will be able to keep income high. A necessary condition is that AESC is higher than a certain threshold, $\underline{R}$, before fossil fuels become exhausted since only in this case will society have the opportunity to set a path of investments that leads the economy towards the higher steady state. Of course, this condition is not sufficient to meet technical efficiency at every moment of time, but it is necessary to enter the attraction basin of the high-income steady state; an investment path able to produce both these two outcomes is the analogue of the one that follows the standard Hartwick rule (Hartwick [4]).

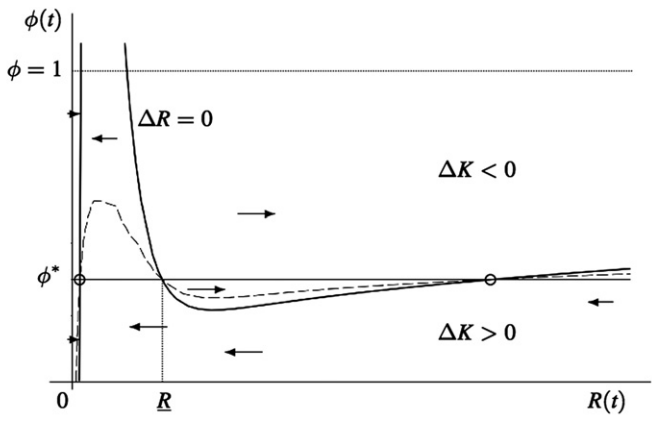


**Fig. 1.** Isoclines of capital and AESC in the plane ($R$, $\phi$).

## 3. Policy implications

The analysis developed so far has not considered welfare, which depends not only on consumption but also on environmental quality, as will be discussed in Section 4. Yet, it is possible to draw some major policy implications. To this end we adopt a pragmatic perspective and imagine that scarcity of fossil fuels enters the agenda only at a given time, $\underline{t}$; previously, energy abundance has been such that developing backstop technologies was not a major issue. What would the policy options be at time $\underline{t}$? Obviously, if policies remain myopically focused on economic growth the economic system would overshoot and collapse when energy becomes binding; at the same time, fostering the development of backstops would require a reduction in capital accumulation and/or consumption. Some simulations will help to illustrate the possible paths involved in different policies undertaken at time $\underline{t}$ and discuss pros and cons of economic growth in the process of accumulation of alternative energy sources.

We suppose that policies are able to affect investments, both regarding the share in alternative sources, $\phi$, and the overall investment share (through propensity to save $1-c$). Furthermore, for illustrative purposes, we also assume that policies are chosen at time $\underline{t}$ and remain unchanged until fossil fuels are no longer sufficient (a point we indicate with $\omega$). At that time society is not free to follow its preferences and must, rather, set the investment in AESC to reach technical efficiency (i.e., no investments in capital until the energy constraint is binding). In other words, we perform some comparative dynamics through a comparison of paths determined by different values of the parameters.

We start by showing, in Fig. 2, the effects of different values of $\phi$ for $t \in [\underline{t}, \omega)$, and we then compare the consumption path in the absence of investment in AESC, $\phi = 0$, with the path delivered by the value of $f$ that makes the growth rate almost zero[8], $\phi = 0.33$. We also draw two other intermediate paths delivered by $\phi = 0.2$ and $\phi = 0.3$. Given that the propensity to save is set at 0.15, expenditure on AESC can be expressed as a percentages of GDP, 0%, 3%, 4.5%, 4.95%, respectively.

When the economy does not invest in AESC ($\phi = 0$), consumption follows path (A). After an initial balanced growth at 3.5% (see equation (10)), the economy collapses, since alternative energy sources have not been developed, and consumption declines to the low equilibrium level, the one consistent with the pre-industrial amount of alternative sources.

Let us now consider path (B) delivered by $\phi = 0.2$. The investment in AESC is not sufficient for the path to enter the basin of attraction of the higher income steady state. Since the growth rate is lower than in path (A), fossil fuels will be exhausted later.

In order to enter the basin of attraction of the higher income steady state, $\phi$ must here be greater than 0.22. Path (C) arises when

[8] For $\phi = 1/3$ capital remains constant since the investment would be equal to capital depreciation. Obviously, it is not possible to run simulations with periodic numbers.

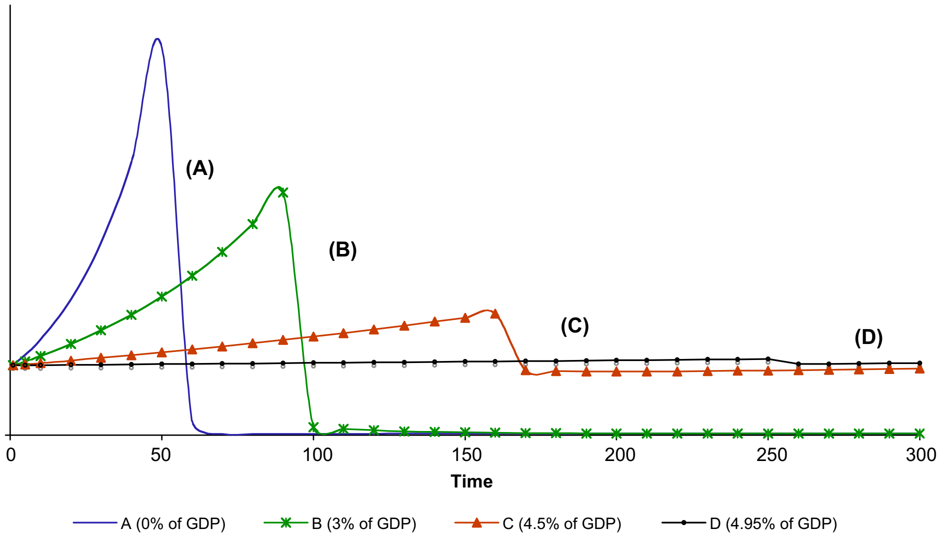


**Fig. 2.** Consumption paths for different levels of investment in AESC. Initial conditions: $K(0)=300$, $X(0)=40{,}000$, $R(0)=10$. Parameters: $c=0.85$, $A=0.7$, $\delta^K=0.07$, $\alpha=1$, $h=0.5$, $\delta^R=0.04$, $\mu=0.75$, $\beta=0$, $\theta=3$, $\eta=4$, $\pi=0.04$.

$\phi=0.3$. In this case, the rate of growth is about 1% for $t\in[\underline{t},\omega)$. At $t=\omega$ exhaustion occurs, part of capital becomes idle, income and consumption fall. However, in contrast to the previous cases, decumulation of capital and accumulation of AESC will, after a while, restore technical efficiency (9) and the economy will start recovering towards the higher steady state. A further increase in $f$ would basically bring economic growth to a halt as in path D, which involves neither a short- nor long-run crisis. Hence, by slowing down capital accumulation, increases in $f$ involve lower consumption and GDP growth rates. Conversely, higher income growth rates for $t<\omega$ will entail a deep short-run crisis and, ceteris paribus, a long-run collapse. Thus, two interrelated policy problems are highlighted: on the one hand, the need to avoid (or minimize) short-run crises, and on the other, the risk of missing the attraction basin of the higher long-run steady state. For the economy depicted in Fig. 2, both the short term energy shortage and the long-term collapse will be avoided by a high share of expenditure in AESC, which will entail low growth rates and extend the time available to build up AESC.

Not surprisingly, the paths are highly sensitive to parameters and initial conditions. As pointed out above, an investment in AESC greater than 22% ($\phi>0.22$) is needed to avoid long-run collapse.[9] Around that threshold even small changes in the parameters of the system are sufficient to shift the path from the sustainable to the unsustainable regime. Hence the resilience of the system is very low if $\phi$ is close to the threshold level.

The initial level of capital is extremely important. If it is too low, growth is needed to provide sufficient resources for take-off in AESC accumulation. Economic sustainability is therefore further endangered and long-run collapse may occur not only for low values but also for high values of $\phi$, since (for a given propensity to save) expenditure in AESC drains economic resources from investment in capital. It may even be the case that no value of $\phi$ exists such that the higher level of long-run consumption can be reached.[10]

In these scenarios the path towards sustainability is very narrow. The path would become wider at higher saving rates as this would lower consumption and increase both the rate of growth and investment in renewables sources. The increase in total savings enlarges the set of choices, helping to avoid both short-run and long-run crises. Hence, lowering consumption growth can widen the sustainability path.

To show this, we simulate a policy experiment aimed at subsidising accumulation in AESC by diverting resources from consumption as well. We assume that a (non distortionary) tax on consumption, $\tau(t)$, is introduced to subsidize AESC. Equation (12) then becomes

$$Y_t = (1-\tau_t)cY_t + (1-\phi_t)(1-c)Y_t + [\phi_t(1-c)+\tau_t c]Y_t. \tag{12a}$$

The tax aims to reach a policy target expressed in terms of percentage of traditional energy sources out of total energy consumption. In the simulations presented here, the target is 10%, that is to say, the tax is levied until fossil fuels decline to below 10% of total energy.

Fig. 3 shows how paths in Fig. 2 change after the introduction of a tax $\tau=0.01$ on consumption[11] As expected, by curbing consumption growth the economic sustainability attraction basin becomes larger since greater quantities of resources are invested in AESC accumulation. This is seen by considering path (b) for which $\phi=0.2$. Without consumption tax, such a level of investment in AESC causes the economy to tend towards the lower steady state; with a small tax, $\phi=0.2$ becomes enough to develop AESC to a level capable of sustaining the economy once fossil fuels have been exhausted. The income growth rate ($g^*=1.4\%$) involves high levels of income before $t=\omega$ which, however, cannot be sustained by the AESC, so that the economy experiences a significant crisis at $t=\omega$. As before, the amplitude of the crisis is reduced by lowering the rate of capital accumulation and diverting a larger part of the investment in capital accumulation to AESC. Path (c) shows the effects of $\phi=0.3$. The crisis occurs much later and is smaller than for path (b); thereafter the economy experiences a prolonged de-growth path towards the higher steady state.

As can be seen by comparing path (C) in Fig. 2 and (c) in Fig. 3, the introduction of a consumption tax facilitates an early start of

[9] In terms of income, 2.5% of GDP should be diverted from investment in capital accumulation to AESC.

[10] A similar result is in Tsur and Zemel ([14], p. 496).

[11] Path A of Fig. 1, for which $\phi=0$, is not included in Fig. 2.

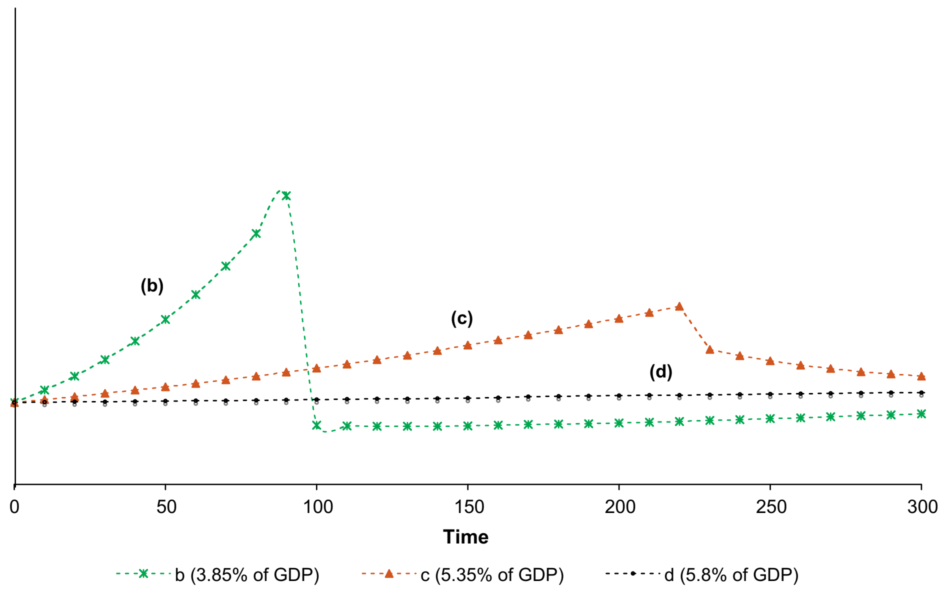


**Fig. 3.** Consumption paths for different levels of investment in AESC: tax introduction. Initial conditions: $K(0)=300$, $X(0)=40{,}000$, $R(0)=10$. Parameters: $c=0.85$, $A=0.7$, $\delta^K=0.07$, $\alpha=1$, $h=0.5$, $\delta^R=0.04$, $\mu=0.75$, $\beta=0$, $\theta=3$, $\eta=4$, $\pi=0.04$, $\tau=0.01$.

the substitution of alternative energy sources for fossil energy, implying that fossil fuels and income growth will last longer.

## 4. The natural environment

So far we have focused merely on economic sustainability. In this section we will consider the issue of environmental sustainability. Similarly to the procedure adopted for the economy, we model the natural environment in a very simplistic manner that focuses only on its regeneration capacity, which is treated as a logistic with critical depensation.[12] The energy used by the economy interacts negatively with the natural environment. The standard assumption (e.g. Tahvonen [28]) is that exhaustible sources have a higher impact per unit of energy, $z_q$, than "alternatives", $z_h$. Hence,

$$S_{t+1} = S_t + \sigma[S_t/S_{\min} - 1][1 - S_t/S_{\max}]S_t - [Q_t z_q + H_t z_h], \tag{17}$$

where $\sigma$ is the intrinsic regeneration rate, $S_{\min}$ is the threshold level below which the ecological system collapses, $S_{\max}$ is the 'natural environment' without anthropic energy use.

Fig. 4 presents the same simulation (and hence the same paths) as Fig. 2 with regard to environmental quality. High rates of economic growth for $t \in [\underline{t},\omega]$ significantly damage the environment; however, for paths (A) and (B), after a dramatic initial crisis, the environment recovers 'thanks' to the collapse of the economy. When $\phi$ is high enough to lead the economy into the basin of attraction of the higher equilibrium, the environment may experience a collapse as for path (C). This is due to the fact that the use of fossil fuel in the first period not only reduces environmental quality, but also reduces the rate of regeneration of the environment to an extent that substitution of alternative energy sources for fossil fuels does not suffice to save the environment. In this respect the tax on consumption, which induces economic growth for a longer time span, may aggravate environmental degradation despite the substitution of alternative energy sources for fossil fuels. A consumption tax alone, as suggested by the previous section, would increase investment in AESC, allowing the prospect of higher availability of energy, higher economic growth and possible environmental unsustainability.[13] Since high rates of economic growth endanger environmental sustainability, any tool that slows down capital accumulation (e.g. high levels of $\phi$) will maintain a safe level of natural environment quality. In conclusion, paths with low-income growth, low consumption and high investment in AESC, such as path (D) (Figs. 2 and 4), are more likely to deliver both environmental and economic sustainability.

## 5. Discussion and concluding remarks

Economic growth is at the centre of economic analysis, the political agenda and public debate. Positive rates of GDP-per-capita growth (i.e., exponential growth) are taken as a physiological feature of contemporary economies. A slowdown causes serious concerns, bolstering fears that the economy cannot withstand the downswing without its turning into a recession. The present crisis shows that a zero growth income rate does not seem to be an attractor of our economies.[14]

However, in the last three decades, doubts have been raised both about the feasibility and desirability of unlimited growth.

[12] The term depensation illustrates the fact that the rate of growth can be a positive function of the renewable stock in some intervals. The adjective critical means that, in addition, the rate of growth is negative for the small level of the stock, in our case smaller than $S_{\min}$. The introduction of the critical depensation curve aims to emphasize that human activities may in fact irreversibly damage the rate of renewable resources regeneration. See, e.g., D'Alessandro [27].

[13] We did not consider the issue of optimality, that is to say, we did not trade-off the benefits from higher consumption, in a utility function, against the welfare losses stemming from lower environmental quality. Such an issue becomes important only after having ascertained that the environmental quality will not fall below unacceptable thresholds.

[14] The importance attributed to growth is based on a number of considerations. An increase in income per capita is regarded as a widening of the set of choices available to individuals, that is, an increase in individual freedom of choice. GDP growth makes it possible to offset the decrease in the demand for labour resulting from the effects of technical change on productivity. Economic growth provides resources for basic research and R&D. Firms tend to invest if they forecast an increase in demand for the goods and services they supply. Expansion of GDP can reduce conflicts in income distribution and facilitate redistribution policies, the provision of public goods, reimbursement of private and government debt, and payment of the interest due on it. GDP growth makes resources available to cope with the increasing burden of pension and health systems springing from soaring life expectancy.

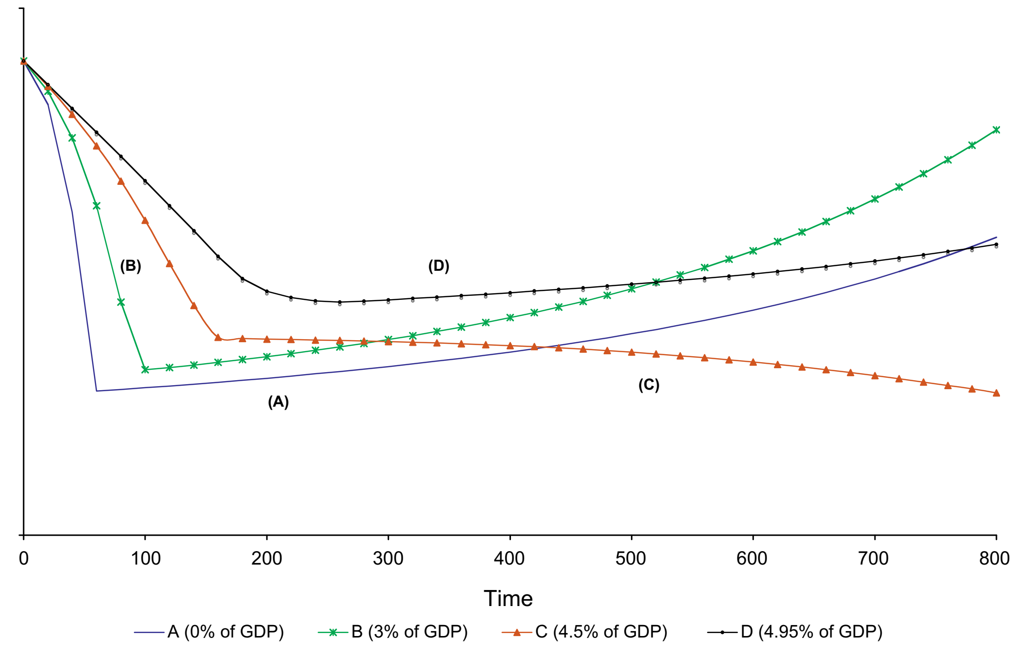


**Fig. 4.** Environmental Quality. Initial conditions: $K(0)=300$, $X(0)=40{,}000$, $R(0)=10$, $S(0)=9000$. Parameters: $c=0.85$, $A=0.7$, $\delta^K=0.07$, $\alpha=1$, $h=0.5$, $\delta^R=0.04$, $\mu=0.75$, $\beta=0$, $\theta=3$, $\eta=4$, $\pi=0.04$, $\tau=0$, $\sigma=0.001$, $S_{\min}=1600$, $S_{\max}=1600$, $z_q=0.14$, $z_h=0.02$.

Numerous authors have contested, on the one hand, the aim of continuous growth that implies increasing economic and social costs stemming from the depletion of natural resources and from pollution, and on the other the GDP definition itself, which does not seem to reflect actual welfare.[15] A wide range of proposals has emerged in response to the increasing need to reconcile economic goals with environmental limits and social issues (see e.g. Victor [30]). These proposals, focusing on the decoupling both of welfare from economic growth and of matter from economic output proposals, have been presented under the labels of de-growth, dematerialization, sustainable development, steady-state economy, eco-development, serene downscaling, qualitative development versus aggregate quantitative growth, and so forth.

The present paper contributes this debate by focusing on the growth implications for the transition from fossil to renewable energy sources. Fossil energy sources have fuelled economic growth ever since the industrial revolution. They are a very special treasure since they provide large quantities of energy at low cost and in concentrated and easy-to-use forms. Our analysis, by elaborating on a classic topic in natural resources economics, shows that the path towards economic and environmental sustainability is possible, although difficult. High levels of income growth, on the one hand, make economic resources available for investment in alternative energy sources, yet on the other, they entail too rapid exploitation of exhaustible energy. Thus diverting investments from physical and human capital to alternative energy sources may not suffice[16]; an effective contribution capable of widening the sustainability window would come from increases in the saving rates and from reduction of consumption growth.

The case of unbounded long-run growth, although deliverable by our model, is not included in our analysis. Two reasons justify such a choice. First, one of the major conclusions, i.e., the need for high saving rates, would not have been affected. Second, unbounded growth is unlikely to be optimal due to environmental limits. These limits would not be binding, as shown by standard growth literature, if one assumed that the whole economy will eventually be able to produce a unit of income with zero matter, that is, if GDP material intensity tends to zero (see Luzzati [31]). In actual fact, historical empirical evidence shows strong correlations between GDP, material throughput and waste/pollution, thereby confirming the idea, emphasised by Georgescu-Roegen, that production consists of extracting and processing matter which very soon becomes waste. Energy is the key factor forging a link between resources and waste/pollution. Energy is both an essential economic input and a major source of environmental pressures since, even if 'clean',[17] it is required for the transformation of matter. Thus, as shown in section 4, exponential GDP growth, which is accompanied and sustained by large amounts of energy and matter, places our society at risk of "poisoning" itself.

To briefly recap, in this paper a dynamic model is developed in order to focus on growth feasibility in an era of increasing scarcity of fossil fuels. Three contributions are made to the existing literature. First, even assuming no substitutability between energy and capital, sustainability is possible. Second, we show that the sustainability window of the economy becomes wider by targeting low GDP growth rates, stimulating investment in alternative energy sources, and curbing consumption growth. High savings channelled towards investments in renewables technology would slowdown the accumulation of capital outside the energy sector, GDP growth, the rate of energy resource depletion, and environmental degradation. Third, we argue that tools affecting the composition of investments in favour of backstop technologies would help to meet environmental sustainability, while policies oriented towards

[15] A distinction must be made here between rich and poor countries. If one may argue that in rich countries a mere quantitative growth of consumption of goods increases costs faster than benefits, in poor countries GDP growth still increases welfare. On this see, Daly ([29], p. 2).

[16] Several different simulations of our model corroborate this observation.

[17] This is not to deny that substitution of alternative for exhaustible energy would involve a relevant reduction in human impact on the natural environment and, in turn, an improvement in human well-being.

stimulating savings and controlling consumption would facilitate economic sustainability.

We acknowledge that there "is more than a passing interest to know which path 'we' are currently on and what would be required to shift to a better one".[18] This difficult and highly debatable question provides a rich agenda for future research.

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