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## Criteria for Assessing Sustainable Development: Theoretical Issues and Empirical Evidence for the Case of Greece

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**Criteria for Assessing Sustainable  
Development: Theoretical Issues  
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# Criteria for Assessing Sustainable Development: Theoretical Issues and Empirical Evidence for the Case of Greece

## Summary

We formulate two kinds of sustainability criteria by using feedback and arbitrary rules for selecting policy variables in non optimizing economies. We show that when policy variables are selected arbitrarily their accounting prices could determine sustainability in addition to the accounting prices of the economy's assets. We use our theoretical framework to obtain estimates of sustainability conditions in real economies. Thus, the paper's contribution consists in developing a systematic theoretical framework for determining value functions, accounting prices and sustainability criteria, under fairly general non-optimizing behavioral rules, and then showing that this framework can be used in applied work to estimate sustainability conditions. Based on our theoretical model, we examined the case of the Greek economy. When there is no binding environmental policy then migration rate, growth of capital per worker and exogenous technical change are strong positive factors for sustainability. When we introduce potential environmental damages due to sulphur dioxide (SO<sub>2</sub>) emissions, our findings indicate that these damages affect negatively the sustainability criterion.

**Keywords:** Sustainability criteria, Non-declining social welfare, Accounting prices, Non optimizing economy, Feedback rule, Arbitrary rule

**JEL Classification:** Q01, O13

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# 1 Introduction

Concerns about environmental deterioration and natural resource depletion have advanced sustainable development as a key concept in policy formulation both at the national and international level. Sustainable development has been the central concept in the World Conservation Strategy published in 1980 and the report of the World Commission on Environment and Development (WCED, 1987) seven years later, and known as the Brundtland Report. Sustainability has also become a central concept in the policy of the European Union.

The most commonly used definition of sustainable development now is that of the Brundtland Report which defines *sustainable development* as *development which meets the needs of the present without compromising the ability of future generations to meet their own needs*. This definition stresses the aspects of intertemporal distribution and intergenerational equity associated with sustainable development but since it embeds many complex economic ideas suffers from tractability, especially when it comes to provide answers to applied questions regarding the sustainability of economics, or the design and evaluation of sustainable development policies.

In the attempt to make the definition of sustainable development operational and useful for the development of sustainability criteria and the design of sustainable policies, many auxiliary definitions have been developed. These definitions identify conditions which when satisfied, an economy can be regarded as following a path of sustainable development. The most prevailing of these definitions (Pezzey 2004) associate sustainable paths with:

1. achieving constant utility (Solow 1974; Hartwick 1977).
2. avoiding any decline in utility (Pearce, Markandya and Barbier, 1989; Pezzey 1992, 1997).
3. avoiding any decline in the present value from time  $t$  and onwards of a Ramsey-Koopmans intergenerational social welfare. (Riley, 1980; Dasgupta and Mäler, 2000; Pemberton and Ulph, 2002; Arrow, Dasgupta and Mäler 2003b).

The concept of *non declining social welfare* or *non declining well being* is used to interpret sustainability as maintenance of social welfare. As shown by Arrow, Dasgupta and Mäler (2003b) sustainable development defined in this context implies, and is implied by, the maintenance of the economy's productive base. This means that each generation should bequeath to each successor at least as large a productive base as it inherited from its predecessors. For this to be achieved, the productive base of the economy should be preserved for the future generations. The productive base includes a list of assets such as *manufactured capital*, *human capital*, *natural capital* and *knowledge*. If genuine investment, defined as the sum of the investment in the above forms of capital, valued at accounting prices, is non-decreasing over time, then social welfare is also non-decreasing and development is sustainable. This concept of sustainability can be regarded as corresponding to the *weak sustainability* concept (Hediger 1999).

One of the advantages of this definition of sustainable development, is that it can be extended to a very general framework which does not depend on whether optimizing or non optimizing behavior is assumed, and which can be used to provide empirical estimations regarding the sustainability conditions for an economy. There is a clear distinction between optimizing and non-optimizing economy first illustrated by Dasgupta and Mäler. *A non-optimizing economy is an economy where the government whether by design or incompetence does not choose policies that maximize intergenerational welfare. The term sustainable development acquires particular bite when it is put to work in imperfect economies, that is economies suffering from weak or even bad governance*<sup>1</sup>.

If we assume that the economy can be described by a dynamic system with the state variables corresponding to assets and the control variables to policy instruments,<sup>2</sup> then the paths of the assets are determined by the way that instruments are chosen. The paths of the state variables determine the value function for the economy, which is social welfare as defined by

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<sup>1</sup>Arrow , Dasgupta and Mäler, 2003(b).

<sup>2</sup>For example in growth models, consumption is a control variable or a policy instrument, and the stock of capital is a state variable..

the Ramsey-Koopmans (or felicity) functional at a given point in time. The value function is a function of the initial values of the assets. If the time derivative of the value function is non negative, then social welfare is also non-decreasing and development is sustainable at this point in time.

The future paths of the assets will be optimal, if controls are chosen optimally in order to maximize the social welfare functional. However, as indicated by Arrow, Dasgupta and Mäler (2003), the economy's value function, and its time evolution is well defined for non-optimal choices of the instruments. This makes possible to define conditions for sustainable development in a general context and to provide a basis for empirical estimations. It is clear that by choosing the structure of the dynamic system describing the economy it is possible to highlight the impact of different factors on sustainability. Arrow, Dasgupta and Maler (2003b) focus on issues such as non-convexities, natural resources, exogenous productivity growth, human capital, while Arrow, Dasgupta and Mäler (2003a), Asheim (2004) link population change with sustainable development in an optimizing framework.

The present paper follows this methodological approach and seeks to provide a well defined theoretical framework for determining sustainability criteria for non optimizing economies, which can also be used to provide a basis for empirical estimations. We believe that since, especially for developing countries, there is no reason to assume that observed data are generated by optimizing processes, the non optimizing framework, properly defined, will be very useful both for purposes of theoretical foundations of sustainability criteria under alternative hypotheses about the structure and the objectives of the economy, and for empirical estimations.

Using the non-optimizing theoretical framework, we derive the (weak) sustainability criterion when controls are chosen according to some feedback rule.<sup>3</sup> We also show that when controls (or policy instruments) are chosen in an arbitrary way which is independent of the stock of assets<sup>4</sup>, the non-declining social welfare sustainability criterion, depends not only on the

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<sup>3</sup>A feedback rule in this context is a behavioral or other arbitrary rule according to which instruments are determined in relation to the values of the state variables.

<sup>4</sup>This implies a non-feedback way of choosing the controls.

growth of the assets and their corresponding accounting prices, but also on the arbitrary paths of the controls. In this case the value function for the economy depends both on current stocks and current flows. These results suggest that in certain cases of non optimizing economies with arbitrary choices of controls, positive genuine investment in assets might not be entirely appropriate for characterizing sustainable development paths. Thus, genuine investment should be adjusted for the growth of the arbitrary chosen policy variables, such as for example emission limits.

This theoretical framework is then applied to data from a real economy with the purpose of providing estimates of sustainability conditions. Thus the paper's contribution, in the long discussion about sustainability, consists of developing a systematic theoretical framework for determining value functions, accounting prices and sustainability criteria, under fairly general non-optimizing behavioral rules, and then showing that this framework can be used in applied work to estimate sustainability conditions.

The rest of the paper is organized as follows. The next section provides the framework for determining sustainability criteria in the case of a non-optimizing economy under a feedback, or an arbitrary rule of policy instruments' choice. In each case the economy is described by a dynamic system, the corresponding value function is defined, and the sustainability criterion for each case is presented. We also provide a definition according to which a policy is promoting sustainability if it implies a relative higher growth of social welfare relative to another policy. We next consider stylized economies without optimizing behavior. In this framework, domestic population growth, migration, labour augmenting technical change, environmental damages associated with pollutant flows generated by economic activities are taken into account in determining the sustainability conditions. In the same context we use a performance standard that determines an upper limit for the emissions of a pollutant and analyze the structure of the value function and accounting prices under an arbitrary environmental policy.

We use our theoretical model to explore the current sustainability conditions within the Greek economy. Our findings suggest that in the case where environmental considerations are not taken into account, or there is

no binding environmental policy, migration, the rate of growth of capital per worker and exogenous technical change are strong positive factors supporting sustainability for the Greek economy. When we introduce potential environmental damages due to sulphur dioxide (SO<sub>2</sub>) emissions, our findings indicate that environmental damages affect negatively the sustainability criterion. In particular sustainability depends on the parameter which reflects the marginal environmental damages in Greece due to SO<sub>2</sub> emissions. For sufficiently high marginal environmental damages the Greek economy is not sustainable according to the non declining social welfare criterion. When considering the case of a possible performance standard in SO<sub>2</sub> emissions- a case corresponding to a binding environmental policy - the accounting value of the emission limit enters the sustainability criterion as suggested by the theoretical model. The effect of the standard on sustainability depends on the relative strength of its effects on production and environmental conditions.

The main empirical finding is that the Greek economy seems to be currently on a sustainable development path if no environmental considerations are taken into account. When such damages are considered, there are negative effects on the sustainability conditions. The last section of the paper concludes.

## 2 Sustainability Criteria in Non-optimizing Economies

Following Arrow, Dasgupta and Maler (2003a) we assume that social welfare at any given time  $t$  is defined by the felicity functional:

$$V_t = \int_t^{\infty} e^{-\delta(\tau-t)} U(\mathbf{x}(\tau), \mathbf{u}(\tau)) d\tau, \tau \geq t \quad (1)$$

where  $\mathbf{x} = (x_1, \dots, x_n)$  denotes a vector of state variables, which can be interpreted as stocks of assets and  $\mathbf{u} = (u_1, \dots, u_m)$  denotes a vector of control variables, which can be interpreted as policy instruments. The function  $U(\mathbf{x}(\tau), \mathbf{u}(\tau))$  can be interpreted as the welfare of the generation living at



time  $\tau$ , under appropriate assumptions about the growth of the population, as it will become clear in the following sections.

The evolution of the economy is described by a system of transition equations linking the state and the control variables.

$$\dot{\mathbf{x}}_\tau = \mathbf{f}(\mathbf{u}(\tau), \mathbf{x}(\tau)) \quad , \quad \mathbf{x}(t) = \mathbf{x}_t \quad , \quad \tau \geq t \quad (2)$$

In an optimizing economy the control paths  $u(\tau)$  are chosen to maximize (1) subject to the constraints imposed by the transition equations (2). In a non optimizing economy the choice of the controls could be determined by a feedback rule  $u(\tau) = g(\mathbf{x}(\tau))$  which might reflect behavioral characteristics of the economy, or some feedback policy rule.

In the Solow model of economic growth, consumption, which is interpreted as a control variable, is a constant fraction of output which is determined, through the aggregate production function, by the capital stock which is the state variable. This constant fraction is a behavioral parameter. Thus in Solow's model consumption is determined by a feedback rule. Furthermore, feedback controls can be chosen to stabilize the economic system, around some desirable steady state,<sup>5</sup> or can be chosen to steer the system to certain state vector in finite time.<sup>6</sup>

Alternatively the choice of controls can be determined in completely *arbitrary way*, by exogenous factors, such as domestic political conditions, historic trends or international conditions. In this case the control paths will be  $\mathbf{u}(\tau) = \bar{\mathbf{u}}(\tau)$

Consider the system of transition equations (2) under the feedback rule, or the arbitrary rule respectively:

$$\dot{\mathbf{x}}_\tau = \mathbf{f}(\mathbf{g}(\mathbf{x}(\tau)), \mathbf{x}(\tau), \mathbf{b}) \quad , \quad \mathbf{x}(t) = \mathbf{x}_t \quad (3)$$

$$\dot{\mathbf{x}}_\tau = \mathbf{f}(\bar{\mathbf{u}}(\tau), \mathbf{x}(\tau), \mathbf{b}) \quad , \quad \mathbf{x}(t) = \mathbf{x}_t \quad (4)$$

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<sup>5</sup>In this case the feedback function is chosen so that the steady state is stable in the Lyapunov sense.

<sup>6</sup>In this case the feedback function is chosen so that the system starting from the initial point  $\mathbf{x}_0$ , reaches the terminal state  $\mathbf{x}_T$ , at finite time  $T$ . It is assumed that the rank conditions for controllability are satisfied.

where  $\mathbf{b}$  is a vector of exogenous parameters. Solutions to these systems, provided they exist, will be in general of the form:

$$\mathbf{x}_\tau = \phi(\tau - t, \mathbf{x}_t, \mathbf{b}), \quad (5)$$

$$\mathbf{x}_\tau = \psi(\tau - t, \mathbf{x}_t, \bar{\mathbf{u}}, \mathbf{b}) \quad (6)$$

Substituting the solutions (5) or (6) into (1) we obtain the value function of the system as a function of the initial state vector  $\mathbf{x}_t$ , and possibly the vector of arbitrary controls  $\bar{\mathbf{u}}(\tau)$ . If the arbitrary control path can be written as:  $\bar{\mathbf{u}}(\tau) = \bar{\mathbf{u}}(\tau - t, \bar{\mathbf{u}}_t)$ ,<sup>7</sup> then the *value function* for the economy can be written as:

$$V_t(\mathbf{x}_t; \mathbf{b}) = \int_t^\infty e^{-\delta(\tau-t)} U(\mathbf{g}(\phi(\tau - t, \mathbf{x}_t, \mathbf{b})), \phi(\tau - t, \mathbf{x}_t, \mathbf{b})) d\tau \quad (7)$$

$$V_t(\mathbf{x}_t, \bar{\mathbf{u}}_t; \mathbf{b}) = \int_t^\infty e^{-\delta(\tau-t)} U(\bar{\mathbf{u}}(\tau - t, \bar{\mathbf{u}}_t), \psi(\tau - t, \mathbf{x}_t, \mathbf{b})) d\tau \quad (8)$$

Accounting prices for asset  $x_i$  or instrument  $\bar{u}_j$  at time  $t$ , are defined as:

$$p_{tx_{it}} = \frac{\partial V_t}{\partial x_{it}}, \quad p_{tu_{jt}} = \frac{\partial V_t}{\partial \bar{u}_{jt}}, \quad (9)$$

respectively.

If we use the non-declining social welfare definition of sustainable development which requires that  $\frac{dV_t}{dt} \geq 0$  we obtain the following result:

**Proposition 1** *Consider a non-optimizing economy with  $x_i$ ,  $i = 1, \dots, n$  assets and  $u_j$ ,  $j = 1, \dots, m$  policy instruments. (i) If policy instruments are chosen following feedback rules associated with the assets of the economy, then sustainability depends on the assets growth and their corresponding accounting prices. (ii) If policy instruments are chosen arbitrarily then sustainability depends both on the assets and the policy instruments growth and their corresponding accounting prices.*

**Proof.** (i) Differentiating (7) totally with respect to time we obtain that

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<sup>7</sup>This implies that the control is chosen according to some arbitrary time dependent rule, for example  $z\%$  increase relative to the previous year.

along a sustainable development path:

$$S_t^F \equiv \frac{dV_t}{dt} = \sum_{i=1}^n \frac{\partial V_t}{\partial x_{it}} \frac{dx_{it}}{dt} + \frac{\partial V_t}{\partial t} \geq 0 \quad (10)$$

(ii) Differentiating (8) totally with respect to time we obtain that along a sustainable development path:

$$S_t^A \equiv \frac{dV_t}{dt} = \sum_{i=1}^n \frac{\partial V_t}{\partial x_{it}} \frac{dx_{it}}{dt} + \sum_{j=1}^m \frac{\partial V_t}{\partial \bar{u}_{jt}} \frac{d\bar{u}_{jt}}{dt} + \frac{\partial V_t}{\partial t} \geq 0 \quad (11)$$

■

It should be noticed that part (ii) of the above proposition shows that in *arbitrary non optimizing economies* - that is economies where instruments are chosen without any relationship to assets - sustainability depends on the growth of these instruments too. Thus the growth of the instruments affects sustainability in addition to the growth of the assets. Since the term  $\sum_{i=1}^n \frac{\partial V_t}{\partial x_{it}} \frac{dx_{it}}{dt}$  represents genuine investment, our results implies that in time autonomous economies, where  $\frac{\partial V_t}{\partial t} = 0$ , positive genuine investment does not imply that development is sustainable. To fully assess sustainability the impacts of instrument should be also taken into account. In this sense Proposition 1 extends previous results about non optimizing economies, where sustainable development depended on genuine investment alone. This result can be associated for example with the introduction of environmental policy, which in real world can be regarded most of the times as arbitrary. Let  $\bar{u}_j$  denote an arbitrary upper limit on emissions, then  $\frac{\partial V_t}{\partial \bar{u}_{jt}}$  can be interpreted as the *accounting price for this limit* and the term  $\frac{\partial V_t}{\partial \bar{u}_{jt}} \frac{d\bar{u}_{jt}}{dt}$  can be interpreted as the *contribution of a changing emission limit to the sustainability criterion*.

If in the arbitrary instrument choice case, instruments are constant so that  $\frac{d\bar{u}_{jt}}{dt} = 0$ , the value function (8) depends on the vector of parameters  $\bar{\mathbf{u}}$  and is written as  $V_t(\mathbf{x}_t; \bar{\mathbf{u}})$ . In this case we can still define the accounting price for the instrument, although the sustainability criterion does not depend

directly on  $\bar{\mathbf{u}}$  but indirectly, through the accounting prices for assets. These accounting prices can be written as:  $p_{tx_i}(\bar{\mathbf{u}}) = \partial V_t(\mathbf{x}_t; \bar{\mathbf{u}}) / \partial x_{it}$ .

It should be noticed that criteria (10), and (11) are defined for the *current period*  $t$ . A positive value for  $S_t^F$  or  $S_t^A$  implies that the economy is *currently* sustainable. The economy will be sustainable for the entire future horizon if:

$$S_\tau^l \geq 0, \text{ for all } \tau \geq t, l = F \text{ or } A \quad (12)$$

Given however the arbitrary choice of instruments, and the associated arbitrary paths for the state variables, this might not be feasible. For example if an arbitrary policy leads to the exhaustion of an essential asset then estimates of (10) or (11) obtained by using the current changes in assets  $dx_{it}/dt$  might indicate that the economy is currently sustainable. The economy will not however be sustainable according to (12). Therefore for empirical purposes which use *current* estimates of the asset's growth rates to obtain an estimate of the criterion (10) or (11), it might be more appropriate to define a "bounded" sustainability criterion, which is defined for a finite time horizon, within which there is a certain confidence in the estimates of the assets' growth rates obtained from the economy's data. The criterion should be reestimated as time goes by, so that possible unexpected effects of the arbitrary policy rules are realized.

Using the definitions (7) and (8) and the argument for a bounded criterion, accounting prices are defined more precisely as :

$$\begin{aligned} p_{tx_{it}} &= \frac{\partial V_t}{\partial x_{it}} = \int_t^T e^{-\delta(\tau-t)} \frac{\partial}{\partial x_{it}} [U(\mathbf{g}(\phi(\tau-t, \mathbf{x}_t, \mathbf{b})), \phi(\tau-t, \mathbf{x}_t, \mathbf{b}))] d\tau \\ p_{t\bar{u}_{jt}} &= \frac{\partial V_t}{\partial x_{it}} = \int_t^T e^{-\delta(\tau-t)} \frac{\partial}{\partial \bar{u}_{jt}} [U(\bar{\mathbf{u}}(\tau-t, \bar{\mathbf{u}}_t), \psi(\tau-t, \mathbf{x}_t, \mathbf{b}))] d\tau \end{aligned} \quad (14)$$

where  $T \leq \infty$ . Furthermore the impact from changes in a parameter  $b_v$  on accounting prices is defined as:

$$\frac{\partial p_{tx_{it}}}{\partial b_v} = \frac{\partial^2 V_t}{\partial b_v \partial x_{it}} = \frac{\partial}{\partial b_v} \left( \frac{\partial V_t}{\partial x_{it}} \right), \quad \frac{\partial p_{t\bar{u}_{jt}}}{\partial b_v} = \frac{\partial^2 V_t}{\partial b_v \partial \bar{u}_{jt}} = \frac{\partial}{\partial b_v} \left( \frac{\partial V_t}{\partial \bar{u}_{jt}} \right)$$

The sustainability criteria (10), (11) along with the definitions of accounting prices (13) and (14) can be used to define a rule for evaluating current policies according to their impact on sustainable development. Consider two alternative *feedback rules*  $(\mathbf{g}_1(\mathbf{x}(\tau)), \mathbf{g}_2(\mathbf{x}(\tau)))$ , or two *arbitrary policies*  $(\bar{\mathbf{u}}_1(\tau), \bar{\mathbf{u}}_2(\tau))$ . Then the corresponding sustainability criteria will be defined through (10) or (11), as  $(S_1^F, S_2^F)$  or  $(S_1^A, S_2^A)$ .

**Definition 1:** A policy either in a feedback form  $g_1(\mathbf{x}(\tau))$  or in an arbitrary form  $\bar{u}_1(\tau)$  is said to promote sustainable development, relative to corresponding policies  $g_2(\mathbf{x}(\tau))$  or  $\bar{u}_2(\tau)$  if:

$$S_1^F \geq S_2^F, S_1^A \geq S_2^A \quad (15)$$

According to this definition a policy is promoting current sustainability if it implies a relative higher growth of social welfare. If policy 2 is the status quo then (15) it can be used to evaluate new policies with respect to their impact on sustainable development. Definition 1 can also be used to assess whether a change in an exogenous parameter promotes sustainable development or not.<sup>8</sup>

### 3 The Value Function and Accounting Prices in a non Optimizing Economy

In this context, our intention is to set up a model which would examine the sustainability of an economy that posses a number of characteristics which are common in reality. We consider therefore economies, where domestic population growth, migration inflows or outflows, labour augmenting technical change and environmental damages associated with pollutant flows generated by economic activities are present. Thus, although we are dealing with a stylized model important characteristics of modern economies such as *migration*, *technical change* and *environmental pollution* are taken into account in determining the sustainability conditions.

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<sup>8</sup>If for example, parameter  $b_m$  changes from  $b_{m1}$  to  $b_{m2}$ , the change promotes sustainability if  $S^F(b_{m2}) \geq S^F(b_{m1})$ .

In particular, given the importance that migration flows have played in the history of economic development, it is interesting to determine the contribution of migration to the sustainability conditions of an economy, along with technical change and environmental pollution. Migration is a phenomenon that affects an economy's population and labor supply. Migration represents gains in population for the destination economy and at the same time losses for the source economy. The movement of a person entails the movement of his human capital and that is the reason why migration also implies some degree of capital mobility<sup>9</sup>.

Let  $M(t)$  be the flow of migrants into the domestic economy. If  $N_l(t)$  is the local population then the migration rate  $m$  is defined as  $m = \frac{M}{N_l}$ . The overall growth of domestic population, or equivalently labor force, is  $\frac{\dot{N}}{N} = \tilde{n}$ , with  $\tilde{n} = n + m$ , where  $n$  is the rate of growth of the domestic labour force and  $m$  is the migration rate. Then, the evolution of the total labour force in the country is determined by:

$$N_\tau = N_t e^{\tilde{n}(\tau-t)}, \tau \geq t \quad (16)$$

If  $m > 0$ , this means that there is an inflow of immigrants in the destination economy whereas if  $m < 0$ , then there is an outflow. Let  $z$  be the capital defined in the broad sense of each person, immigrant or emigrant. If  $z = 0$ , this means that the immigrants or the emigrants do not come with human capital such as special skills or education, or any other type of capital, and this can be interpreted as migration which does not support any type of capital movement. In this case there is only labour force change and not human or physical capital mobility. If  $z \neq 0$  that means that migration also includes some kind capital mobility.

Capital accumulation in our stylized economy is described by using the standard Solow model. We assume that exogenous technical change of labour augmenting type (Harrod neutral technical change) is present. This means that the aggregate production function can be written as  $Y = F(K, AN)$ ,

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<sup>9</sup>See for example Barro and Sala-i-Martin (1995).

where  $\frac{\dot{A}}{A} = g$ , which is the rate of exogenous technical change and  $\hat{L} = AN$  which is effective labour. Using the standard Cobb-Douglas production function  $Y = K^a (AN)^{1-a}$  the accumulation of capital, measured in per effective worker terms, with  $\hat{k} = \frac{K}{AN}$ , with  $\hat{y} = \hat{k}^a$  and  $m$  defined as the migration rate, is given by (Barro and Sala-i-Martin, 1995):

$$\dot{\hat{k}}_t = s\hat{k}_t^a - (\eta + \delta + g)\hat{k}_t - m\hat{k}_t + z$$

setting  $z = 0$  we obtain:

$$\dot{\hat{k}}_t + (\eta + \delta + m + g)\hat{k}_t = s\hat{k}_t^a \quad (17)$$

Then capital accumulation is described by a Bernoulli differential equation which can be solved to obtain:<sup>10</sup>

$$\hat{k}_\tau = \left[ \left( \hat{k}_t^{1-a} - \frac{s}{\omega} \right) e^{-(1-a)\omega(\tau-t)} + \frac{s}{\omega} \right]^{\frac{1}{1-a}}, \tau \geq t, \omega = (\eta + \delta + m + g) \quad (18)$$

Since in the Solow model consumption is a fixed proportion of output,<sup>11</sup> we have, in per effective worker terms:

$$\hat{c}_\tau = (1 - s)\hat{k}_\tau^a \quad (19)$$

or

$$\hat{c}_\tau = (1 - s) \left[ \left( \hat{k}_t^{1-a} - \frac{s}{\omega} \right) e^{-(1-a)\omega(\tau-t)} + \frac{s}{\omega} \right]^{\frac{a}{1-a}} \quad (20)$$

Environment is introduced into the model by the variable  $P$ , which is interpreted as pollution which affects utility in a negative way. Then the utility function becomes a function of per capita consumption  $c_\tau$  and total pollution  $P_\tau$  and is assumed, as it is common in this type of analysis, to have

<sup>10</sup>For the solution see the Appendix.

<sup>11</sup>In the terminology of the previous section, consumption is a feedback control.

the following separable specification:

$$U(c_\tau, P_\tau) = -c_\tau^{-(\sigma-1)} - D(P_\tau) \quad (21)$$

In (21)  $-\sigma$  is the elasticity of marginal utility, with  $\sigma > 1$ , and  $P_\tau$  can be interpreted as pollution which creates disutility. Therefore  $D(P_\tau)$  can be interpreted as a damage function assumed strictly increasing and convex. We specify the damage function as  $D(P_\tau) = \theta P_\tau^\gamma$  with  $\theta > 0$  and  $\gamma \geq 1$ . Since the production structure is determined in per effective worker terms, we need to specify the utility function (21) in per effective worker terms. If we define consumption per effective worker as  $\hat{c} = \frac{C}{AN}$ , from the definition of per capita consumption we have:

$$\frac{C_\tau}{N_\tau} = c_\tau = \hat{c}_\tau A_t e^{g(\tau-t)}.$$

then we have:

$$u(c_\tau) = -c_\tau^{-(\sigma-1)} = -(\hat{c}_\tau A_t e^{g(\tau-t)})^{-(\sigma-1)}$$

and the utility function (21) becomes:

$$U(c_\tau, P_\tau) = -(\hat{c}_\tau A_t e^{g(\tau-t)})^{-(\sigma-1)} - \theta P_\tau^\gamma \quad (22)$$

We assume that pollution is of the flow type and that the flow of pollution is related to output production by a strictly increasing function  $P_\tau = \mu(Y_\tau)$ . In terms of the discussion in section 2, pollution is also a form of a feedback control, since by using the production function to substitute for output it can be written as a function of the capital stock. The feedback rule can be associated with technical conditions which determine completely, in the absence of environmental policy, the evolution of emissions. The  $\mu(\cdot)$  function can be further specified as:

$$P_\tau = \mu Y_\tau^\beta e^{xt}, \mu > 0, \beta > 0 \quad (23)$$



where  $x$  reflects technical change in pollution generation. A negative  $x$  reflects pollution reducing technical change. Since in per effective worker terms,  $Y_\tau = \hat{y}_\tau A_\tau N_\tau = \hat{k}_\tau^a A_\tau N_\tau e^{(g+\tilde{n})(\tau-t)}$ ,  $\tilde{n} = n + m$ , by substituting  $Y_\tau$  in (23) and using (18), (20), and (22) the utility flow in per effective worker terms is specified as:

$$U(\hat{k}_t, N_t, A_t) = -(\hat{c}_\tau A_\tau e^{g(\tau-t)})^{-(\sigma-1)} - \theta \left[ \mu \left( \hat{k}_\tau^a A_\tau N_\tau e^{(g+\tilde{n})(\tau-t)} \right)^\beta e^{x(\tau-t)} \right]^\gamma \quad (24)$$

The flow of total utility in the economy is  $N_\tau U(c_\tau, P_\tau)$ , therefore *the value function* for the economy, using (24) becomes:<sup>12</sup>

$$V_t = \int_t^T e^{-\rho(\tau-t)} N_\tau U(\hat{k}_\tau, N_\tau, A_\tau) dt, T \leq \infty, N_\tau = N_t e^{\tilde{n}(\tau-t)} \quad (25)$$

It should be noted that the value function depends only on the current values of state variables of the problem  $(\hat{k}_t, N_t, A_t)$  and the parameters describing the structure of the economy.

Following (13) of the previous section the current accounting prices are defined as follows:

$$p_{t\hat{k}_t} = \frac{\partial V_t}{\partial \hat{k}_t}, p_{tN_t} = \frac{\partial V_t}{\partial N_t}, p_{tA_t} = \frac{\partial V_t}{\partial A_t} \quad (26)$$

Since  $\hat{k} = \frac{k}{A} = \frac{K}{AN}$ ,  $k = \frac{K}{N}$  the accounting price of capital in physical units and per capita units is defined respectively as:

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<sup>12</sup>A more complex structure would require, additional transition equations for, say, natural resources (depletable or renewable), stocks of pollutants, human capital and so on. In this case the value function would depend on the current values of the stocks for these assets. The development of such a dynamic system, with the associated feedback or arbitrary rules and its solution, so that the value function can be defined in an operational way, is an area for future research.

$$p_{tK_t} = \frac{\partial V_t}{\partial \hat{k}_t} \frac{\partial \hat{k}_t}{\partial K_t} = \frac{1}{A_t N_t} p_{t\hat{k}_t} \quad (27)$$

$$p_{tk_t} = \frac{\partial V_t}{\partial \hat{k}_t} \frac{\partial \hat{k}_t}{\partial k_t} = \frac{1}{A_t} p_{t\hat{k}_t} \quad (28)$$

It should be noted that in this case there is no specific accounting price for pollution since pollution is not a stock, but the impact of pollution is realized through the accounting price of capital  $p_{t\hat{k}_t} = \partial V_t / \partial \hat{k}_t$  which depends on the parameters of the damage function.

### 3.1 Sustainability in the presence of environmental policy.

Assume that the environmental policy is expressed through a *performance standard* that determines an upper limit for the emissions of the firms. Since the emission function of the representative firm can be written as:

$$P_\tau = \mu Y_\tau^\beta e^{x(\tau-t)} = \mu (\hat{y}_\tau AN)^\beta e^{x(\tau-t)} = \phi \left( f \left( \hat{k}_\tau \right) AN \right) e^{x(\tau-t)}, \phi' > 0 \quad (29)$$

the emission limit will take the form:

$$P_\tau \leq \bar{P} \quad (30)$$

The *profit function* of the representative firm can be written in per effective worker terms as:

$$AN \left[ f \left( \hat{k}_\tau \right) - (r + \delta) \hat{k}_\tau - w e^{-g(\tau-t)} \right] \quad (31)$$

The firm considers the interest rate  $r$  and the wage rate  $w$  as fixed and chooses capital, for any fixed level of effective labour  $AN$  to maximize (31)

subject to (30). The Lagrangian for the problem is:

$$\mathcal{L} = AN \left[ f \left( \hat{k}_\tau \right) - (r + \delta) \hat{k}_\tau - w e^{-g(\tau-t)} \right] + \lambda \left[ \bar{P} - \phi \left( f \left( \hat{k}_\tau \right) AN \right) e^{x(\tau-t)} \right] \quad (32)$$

with Kuhn-Tucker conditions for an interior solution to the problem imply:

$$f' \left( \hat{k}_\tau \right) \left[ 1 - \lambda \phi' e^{x(\tau-t)} \right] = r + \delta, \hat{k}_\tau^* > 0 \quad (33)$$

$$\lambda \left[ \bar{P} - \phi \left( f \left( \hat{k}_\tau^* \right) AN \right) e^{x(\tau-t)} \right] = 0, \lambda \geq 0 \quad (34)$$

If the emission constraint is not binding then  $\lambda = 0$  and the solution  $\hat{k}_\tau$  is obtained by the usual condition  $f' \left( \hat{k}_\tau \right) = r + \delta$ .<sup>13</sup> Under concavity of the production function and Inada conditions a unique solution always exists. If  $\lambda > 0$  then the constraint is binding and the capital stock is determined as a function of the emission limit by the solution of:

$$\bar{P} = \phi \left( f \left( \hat{k}_\tau \right) AN \right) e^{x(\tau-t)}, \text{ as} \quad (36)$$

$$\hat{k}_\tau^* = \psi \left( \bar{P}; AN, e^{x(\tau-t)} \right), \text{ with } \frac{d\hat{k}_\tau}{d\bar{P}} > 0 \quad (37)$$

Thus a more stringent emission limit will reduce the stock of capital. This can be also seen from (33). A positive  $\lambda$  shifts the marginal product curve  $f' \left( \hat{k}_\tau \right)$  to the left. As a result  $\hat{k}_\tau^* < \hat{k}_\tau$  and the binding performance standard reduces the equilibrium stock of capital. It can be also noticed that if  $x < 0$  so that we have emission saving technical change then the reduction of the equilibrium stock of capital, under the performance standard will be smaller, the larger this type of technical change is. Since capital stock is relatively reduced from a binding performance standard or equivalently from a more stringent performance standard, output is also reduced ceteris paribus. This reduction is determined as  $f \left( \hat{k}_\tau \right) - f \left( \hat{k}_\tau^* \left( \bar{P} \right) \right)$ .

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<sup>13</sup>Zero profits for any given wage  $w$ , require that

$$\left[ f \left( \hat{k}_\tau \right) - \hat{k}_\tau f' \left( \hat{k}_\tau \right) + \lambda \phi' f' \left( \hat{k}_\tau \right) e^{x(\tau-t)} \right] e^{-g(\tau-t)} = w \quad (35)$$

Let  $f\left(\hat{k}_\tau^*(\bar{P})\right)$  be the output of the economy under the performance standard  $\bar{P}$ . Then consumption in per effective worker terms is defined as  $\hat{c}_\tau = (1 - s)y_t$ , and since  $y = f\left(\hat{k}_\tau^*(\bar{P})\right)$ , we have:

$$\hat{c}_\tau = (1 - s) f\left(\hat{k}_\tau^*(\bar{P})\right) = \hat{c}_\tau(\bar{P}) \quad (38)$$

then the per capita utility flow in the economy will be:

$$U\left(\hat{c}_\tau, \bar{P}\right) = \left[-\left(\hat{c}_\tau A_t e^{g(\tau-t)}\right)^{-(\sigma-1)} - \theta \bar{P}^\gamma\right] \quad (39)$$

In empirical applications, where the main purpose will be to examine the impact of a performance standard on the sustainability of the economy a reliable estimate of  $f\left(\hat{k}_\tau^*(\bar{P})\right)$  is unlikely due to data limitations. In this case an approach could be to assume that the reduced output under the binding standard is approximately proportional to the output obtained without a limit on emissions. This means that we set:

$$f\left(\hat{k}_\tau^*(\bar{P})\right) \approx (1 - z_{\bar{P}}) f\left(\hat{k}_\tau^0\right) \quad (40)$$

which implies that  $f\left(\hat{k}_\tau^0\right)$  can be interpreted as full capacity output, without environmental constraints.<sup>14</sup> Under the Cobb-Douglas assumption, we have:

$$\hat{y} = (1 - z_{\bar{P}}) \hat{k}^a$$

In this case the accumulation of capital in per effective worker terms is:

$$\dot{\hat{k}}_t = s(1 - z_{\bar{P}}) \hat{k}_t^a - (\eta + \delta + g) \hat{k}_t - m \hat{k}_t + z$$

setting  $z = 0$  as before we obtain:

$$\dot{\hat{k}}_t + (\eta + \delta + m + g) \hat{k}_t = s(1 - z_{\bar{P}}) \hat{k}_t^a \quad (41)$$

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<sup>14</sup>For an estimate of the proportion of output lost due to environmental regulation in the US economy see Jorgenson and Wilcoxon (1998)

The solution of this Bernoulli equation is<sup>15</sup>:

$$\hat{k}_\tau = \left[ \left( \hat{k}_t^{1-a} - \frac{s(1-z_{\bar{P}})}{\omega} \right) e^{-(1-a)\omega(\tau-t)} + \frac{s(1-z_{\bar{P}})}{\omega} \right]^{\frac{1}{1-a}} \quad (42)$$

$$\omega = \eta + \delta + m + g \quad (43)$$

Therefore,  $\hat{c}_\tau = (1-s)(1-z_{\bar{P}})\hat{k}_\tau^a = \hat{c}_\tau(\hat{k}_\tau; z_{\bar{P}})$ , and the value function for the economy becomes:

$$V_t = \int_t^T e^{-\rho(\tau-t)} N_t U(\hat{k}_\tau, N_\tau, A_\tau, \bar{P}; z_{\bar{P}}) dt, T \leq \infty \text{ or} \quad (44)$$

$$V_t = - \int_t^T e^{-\rho(\tau-t)} N_t \left[ \left( \hat{c}_\tau(\hat{k}_\tau; z_{\bar{P}}) A_t e^{g(\tau-t)} \right)^{-(\sigma-1)} - \theta \bar{P}^\gamma \right] dt, T \leq \infty$$

The current accounting price for the performance standard  $\bar{P}$  can be calculated as:

$$p_{t\bar{P}} = \frac{\partial V_t}{\partial \bar{P}} = \int_t^T e^{-\rho(\tau-t)} \frac{\partial}{\partial \bar{P}} U(\hat{k}_\tau, N_\tau, A_\tau, \bar{P}; z_{\bar{P}}) dt$$

Thus, there is a specific accounting price for the arbitrary control  $\bar{P}$ .

## 4 The Sustainability Criterion in a Non Optimizing Economy

Based on the results of Proposition 1 the sustainability criterion for our stylized economy with produced capital, exogenous technical change, migration and pollution which, in the absence of environmental policy, can be expressed in a feedback form, implies that this economy follows a weakly sustainable path at time  $t$  if:

$$\dot{V}_t = p_{K_t} \dot{K} + p_{N_t} \dot{N} + p_{A_t} \dot{A} \geq 0$$

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<sup>15</sup>See Appendix for details

Dividing by  $Nk$ , where  $k = \frac{K}{N}$ , using the fact that  $\dot{k} = \frac{d(K/N)}{dt} = \frac{\dot{K}}{N} - \frac{\dot{N}}{N}k$ , and that the accounting price for capital in physical terms is related to the accounting price of capital in per effective worker terms by (27) we obtain:

$$S_{1t} = \frac{\dot{V}_t}{N_t \hat{k}_t} = \frac{p_{t\hat{k}_t}}{A_t N_t} \left( \frac{\dot{k}}{k} + \frac{\dot{N}}{N} \right) + p_{tN_t} \frac{\dot{N}}{N} \frac{1}{k_t} + p_{tA_t} \frac{\dot{A}}{A} \frac{A_t}{N_t k_t}$$

where  $S_{1t}$  measures the change in the value of the economy per unit of produced capital stock at time  $t$ . Thus  $S_{1t}$  could be interpreted as the rate of return on produced capital measured in terms of social welfare. It is clear that by multiplying  $S_{1t}$  by the current stock of capital we obtain a measure of current genuine investment. Using as before  $\frac{\dot{A}}{A} = g$ ,  $\frac{\dot{N}}{N} = \tilde{n} = n + m$ , with  $m \stackrel{\leq}{\geq} 0$  depending on the migration rate, and denoting the rate of growth of per capital per worker  $\frac{\dot{k}}{k} = v$ , development is currently sustainable if:

$$S_t^F = \frac{p_{t\hat{k}_t}}{A_t N_t} (v + \tilde{n}) + p_{tN_t} \tilde{n} \frac{1}{k_t} + p_{tA_t} g \frac{1}{k_t} \frac{A_t}{N_t} \geq 0 \quad (45)$$

When an arbitrary environmental policy in the form of the emission limit  $\bar{P}$  is present the criterion becomes:

$$\dot{V}_t = p_{K_t} \dot{K} + p_{N_t} \dot{N} + p_{A_t} \dot{A} + p_{\bar{P}_t} \frac{d\bar{P}}{dt} \geq 0 \quad \text{or} \quad (46)$$

$$S_{2t} = \frac{p_{\hat{k}_t}}{A_t N_t} (v + \tilde{n}) + p_{N_t} \tilde{n} \frac{1}{k_t} + p_{A_t} g \frac{1}{k_t} \frac{A_t}{N_t} + p_{\bar{P}_t} \pi \frac{1}{k_t} \frac{\bar{P}_t}{N_t} \geq 0 \quad (47)$$

where  $\pi$  is *the rate of growth of the* emission limit, with  $\pi < 0$  indicating that environmental policy becomes gradually more stringent and  $\pi > 0$  indicating that environmental policy is becoming more lax. As before, by multiplying  $S_{2t}$  by the current stock of capital we obtain a measure of current genuine investment. In this case genuine investment is adjusted for the changes in environmental policy, a required adjustment that has not been noticed in earlier literature.

## 5 Exploring Sustainability Conditions within the Greek Economy

The stylized model developed above is used to explore the current sustainability conditions within the Greek economy. To apply the model we need estimates of the parameters required to define the value functions (25) or (44).

Our approach was to estimate, using econometric estimations, the parameters that correspond to structural relations and to assign plausible values to those parameters that econometric estimation was not possible. For these parameters we used sensitivity analysis to ensure the robustness of our results.

The parameters required in order to estimate criterion (45), (47) are:  $n$  the rate of growth of domestic labour force and  $m$  the migration rate;  $v$  the rate of growth of capital per worker;  $g$  the rate of growth of labour augmenting technological change;  $s$  which expresses savings as proportion of Greek GDP in the period analyzed;  $a$  which is the parameter of the production function reflecting the elasticity of capital input;  $\rho$  which represents the discount rate;  $\sigma$  the elasticity of marginal utility the value of which reflects preferences towards equality in income distribution;  $\delta$  which is the depreciation rate;  $\mu$  and  $\gamma$  which are the parameters of the postulated damage function  $D(P_\tau) = \theta P_\tau^\gamma$ ;  $\mu$ ,  $\beta$  and  $x$  which are the parameters of the emission function  $P_\tau = \mu Y_\tau^\beta e^{xt}$ ; and finally when we need to examine the impact of an emission limit, the potential reduction in  $GDP$  due to the emission limit, is the parameter  $z_{\bar{P}}$ . It was assumed in the absence of any data that  $z$ , the capital brought in Greece by migrants, was zero.

The fundamental data for the Greek economy were *GDP*, *Capital*, and *Labour*,<sup>16</sup> measured in million 1990US\$ and thousands of workers respectively, using data from the Penn- tables for the period 1965-1990. We obtain the average annual growth rates of these variables in physical units and in

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<sup>16</sup>In modeling the production structure we consider labour augmenting technical change. We do not introduce human capital so our sustainability characteristics do not include human capital aspects but include labour augmenting technical change.

per capita terms during the sample period by estimating the relationship:

$$\ln x_t = a_o + a_1 t \quad (48)$$

where  $x_t$  is the variable of interest and  $t$  takes values  $t = 1, \dots, T$  during the sample period.<sup>17</sup>

The estimates of the growth rates for the variable of interest in physical and in per worker terms are shown in the tables below.

Rates of Growth 1965-1990	% per year
Capital ( $K$ )	5.55
GDP ( $Y$ )	3.64
Labour ( $N$ )	0.6

Next we estimated the *rates of growth in per worker terms* and the results are presented in the table below:

Rates of Growth in per worker terms 1965-1990	% per year
Capital, $k$	4.95
GDP, $y$	3.035

The basic structural relationships were the aggregate production function for the economy and the emission function (23).

The estimates from the production function are used to determine the elasticity of capital with respect to output, which is the parameter  $a$ , and the rate of labour augmenting technical change  $g$ . We assume the existence of a constant returns to scale Cobb-Douglas long run aggregate production function for the Greek economy, defined over man made capital and effective labour input, which takes the form:

$$Y_t = BK^a (Le^{gt})^{1-a}$$

or in per worker terms:<sup>18</sup>

$$y_t = Bk_t^a e^{qt}, \quad q = g(1 - a)$$

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<sup>17</sup>Relationship (48) corresponds to the standard exponential growth model  $x_t = A_o e^{a_1 t}$ .

<sup>18</sup>It is clear the in per worker terms this function becomes  $\hat{y}_t = B\hat{k}_t^a$ , which is the function used with  $B = 1$  in the previous sections.



The statistical model can be written as:

$$\ln y_t = \ln B + a \ln k_t + qt + \varepsilon_t, t = 1, \dots, T \quad (49)$$

where  $\varepsilon_t$  is the usual error term. The production function (49) can be interpreted as a long run equilibrium relationship that shifts in time as it is affected by technical change. To test for the existence of such equilibrium relationship we test for the existence of a cointegrating relationship. The Johansen cointegration test<sup>19</sup> suggest that both the trace and the maximum eigenvalue tests indicate one cointegrating relationship with constant and deterministic trend at 5% level.

Next we use OLS to estimate (49). The results are summarized in the table below:

<b>Variable</b>	<b>Coefficient</b>	<b>Std. Error</b>	<b>t-Statistic</b>
$\ln B$	1.438115	0.187444	7.672226
$\ln k$	0.402501	0.080129	5.023150
$t$	0.005392	0.003080	1.750943
R-squared	0.957372		
Adjusted R-squared	0.952636		
Durbin-Watson stat	1.175040		

These results imply that the elasticity of capital input is  $a = 0.4025$ , while the rate of labour augmenting technical change is  $g = \frac{q}{1-a} = 0.009$  or 0.9% annually.

For the emission function we used sulfur dioxide emissions ( $SO_2$ ), which is a pollutant with flow characteristics, measured in annual emissions in kilotons covering the period 1980 – 1999, (Source: European Environment Agency, Copenhagen). These emission were related to output, assuming an emission function of the constant elasticity form. (23).The results we obtained were the following:

<b>Variable</b>	<b>Coefficient</b>	<b>Std. Error</b>	<b>t-Statistic</b>
constant	4.156018	2.289511	1.815243
$\ln Y$	0.225308	0.241803	0.931786

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<sup>19</sup>See software package e-views.

AR(1)	0.745520	0.084558	8.816671
R-squared	0.906529		
Adjusted R-squared	0.894845		
Durbin-Watson stat	2.176287		

The emission relationship was regarded as a technological relationship. Estimates were corrected for first order serial correlation, which turned out to be highly significant. A trend term which could indicate technical change associated with SO<sub>2</sub> emissions was highly insignificant.

To complete the set of required parameters we require the migration flow  $m$ , the marginal propensity to save  $s$ , the discount rate  $\rho$ , the depreciation rate  $\delta$ , the elasticity of marginal utility  $\sigma$ , the parameters of the damage function, and the parameter  $z_{\bar{p}}$  when we examine the impact of an emission limit.

For the migration rate a recent study (Lianos 2003)<sup>20</sup> indicates that between 1991 and 2001 the number of immigrants who entered the Greek economy is around 630.000, assuming an average annual flow of  $M(t) = 60.000$  and dividing by the average value of number of workers in the same period of  $N(t) = 4000000$  we arrive at an estimate of  $m = \frac{M}{L} = 0.015$ .

For the marginal propensity to save we use the average value for the period 1970 - 1990 of savings as a proportion of GDP, with  $s = 0.21$ .<sup>21</sup> The depreciation rate was taken  $\delta = 3\%$  following Mankiw, Romer and Weil (1992); the discount rate at  $\rho = 3\%$ ; and the elasticity of marginal utility at  $\sigma = 3$  which reflects relatively strong preferences towards equal income distribution. The parameter  $\gamma$  of the damage function was set,  $\gamma = 1$ . This implies a linear damage function in which  $\theta$  reflects marginal damages. Since the units of output and consumption were million US \$,  $\theta$  reflects the environmental damages in Greece, in million US\$, from the emissions of one kiloton of sulphur dioxide in a year. In the absence of any information the value of  $\theta$  was taken in the interval  $[10^{-6}, 10^{-3}]$  indicating damages from 1 US\$ to 1000 US\$ per kiloton of sulphur dioxide a year. For the parameter

<sup>20</sup>KEPE, Study 51, T. Lianos . Sygxroni Metanasteusi stin Ellada: Oikonomikh Diereynish.

<sup>21</sup>For the date see "The Greek Economy in Figures 2002". page 105.

$z_{\bar{p}}$  there is no information for the Greek economy. Jorgenson and Wilcoxon (1998), using a computable general equilibrium approach, estimated the cost of all environmental restrictions for the US economy, to be 2.592% of real GNP, so we set  $z_{\bar{p}}$  at a conservative value of 1%.

The parameter values used are summarized in the following table:

<i>Parameter</i>	$n$	$m$	$v$	$g$	$s$	$a$	$\rho$	$\delta$	$\sigma$
<i>Value</i>	0.006	0.015	0.0495	0.009	0.21	0.4025	0.03	0.03	3
<i>Parameter</i>	$\beta$	$\mu$	$x$	$\gamma$	$\theta$	$z_{\bar{p}}$			
<i>Value</i>	0.225	4.146	0	1	$[10^{-6}, 10^{-3}]$	0.01			

Using the above parameters accounting prices were calculated with numerical integration of the derivatives of the value function<sup>22</sup> for a time horizon of 100 years.<sup>23</sup> *Two set of results were obtained*, one set corresponding to emissions determined by a feedback rule through the emission function and using the criterion (45) and another one regarding the 1999 sulphur dioxide emissions as an upper emission limit and using (47).

Table 1 below shows accounting prices and the sustainability criterion for different marginal damages, *when there is no binding environmental policy*.

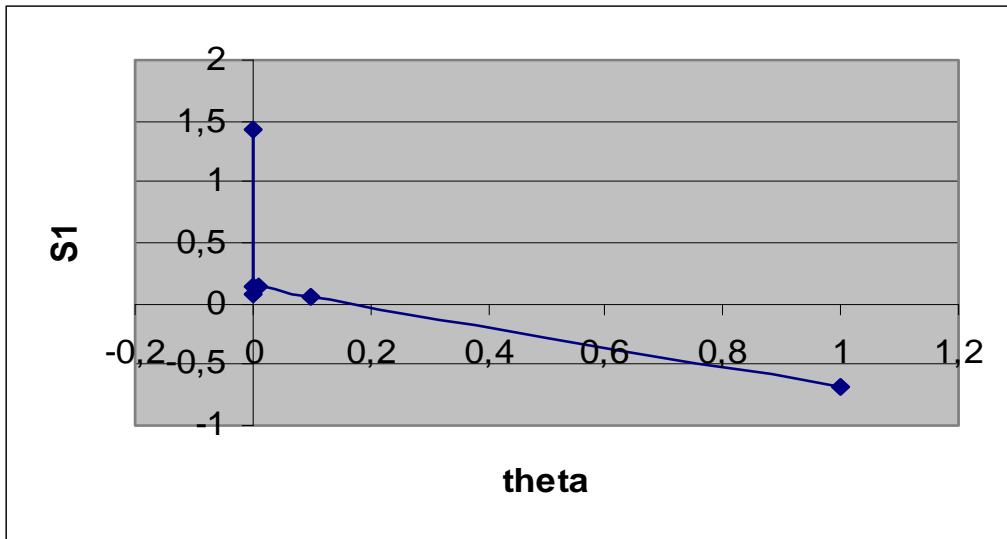
Table1: Accounting Prices and the Sustainability Criterion

$m$	$\theta$	$p_K$	$p_N$	$p_A$	$S_1$
0	0	0.0011216	-0.0464493	315.511	0.00007839
0.015	0	0.00238486	-0.125464	852.225	0.00142968
0.015	$10^{-6}$	0.00238326	-0.126324	851.689	0.0001411
0.015	$10^{-5}$	0.00237046	-0.134064	846.860	0.00013461
0.015	$10^{-4}$	0.00224252	-0.21147	798.574	0.00005950
0.015	$10^{-3}$	0.00096316	-0.985523	315.712	-0.0006916

We can observe from the table above that for marginal environmental damages below 1000 US\$ per kiloton the Greek economy is currently on a sustainable path. Furthermore it is clear that migration has played an important role in the current sustainability conditions of the Greek economy,

<sup>22</sup>Numerical results were obtained by using *Mathematica*.

<sup>23</sup>This time horizon is quite long. Thus the results should be interpreted as if the fundamental structure of the economy would remain approximately the same within this horizon. Of course estimates of the accounting prices for smaller time horizons can be easily obtained.



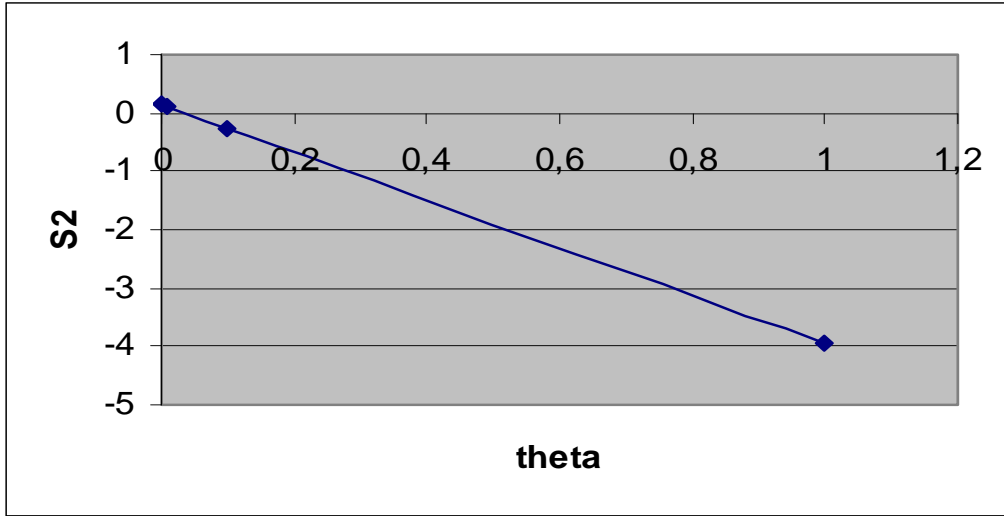
since the criterion is reduced substantially when we set  $m = 0$ . Furthermore the accounting prices have the expected signs and the sustainability criterion is declining in environmental damages as expected. For sufficiently high marginal environmental damages the criterion becomes negative. Thus the sustainability conditions for the Greek economy are sensitive to environmental damages. Multiplying the  $S_1$  column by the stock of capital we can obtain an estimate of the genuine investment in Greece for different values of marginal environmental damages.

The following diagram represents the values of  $\theta$  and the sustainability criterion  $S_1$ .<sup>24</sup>

Table 2 shows accounting prices and the sustainability criterion *as if* the emission limit for sulphur dioxide has been set at the 1999 emission level, which was 541 kilotons. Values have been calculated for  $m = 0.015$  and  $z = 0.01$

Table 2: Accounting Prices and the Sustainability Criterion under an Emission Limit

<sup>24</sup>All values have been multiplied by 1000 for the purpose of a better presentation.



$\theta$	$p_K$	$p_N$	$p_A$	$p_{\bar{P}}$	$p_{z_{\bar{P}}}$	$S_2$
$10^{-6}$	0.002445	-0.134	837.99	-0.03396	-1107.63	0.0001412
$10^{-5}$	0.002445	-0.183	837.99	-0.33963	-1107.63	0.0001047
$10^{-4}$	0.002445	-0.669	837.99	-3.33963	-1107.63	-0.000266
$10^{-3}$	0.002445	-5.559	837.99	-33.963	-1107.63	-0.003962

In the above table the column  $p_{\bar{P}}$  refers to  $\frac{\partial V}{\partial \bar{P}}$  which is the accounting price for the emission standard. This price is negative as expected, since an increase in  $\bar{P}$  that is a more lax environmental policy, is expected to reduce the economy's value, if  $z_{\bar{P}}$  remains constant. The column  $p_{z_{\bar{P}}}$  refers to  $\frac{\partial V}{\partial z_{\bar{P}}}$  which is negative as expected. This means that if the cost of the standard in terms of output foregone increases then the economy's value is reduced ceteris paribus. Since lax standard is expected to reduce  $z_{\bar{P}}$  the final outcome from a change in the performance standard on the value of the economy depends on the expression  $\frac{\partial V}{\partial \bar{P}} d\bar{P} + \frac{\partial V}{\partial z_{\bar{P}}} dz_{\bar{P}}$ . Again as expected the sustainability criterion is declining in marginal environmental damages. The following figure shows again the  $\theta, S_2$  relationship for the performance standard case.

## 6 Concluding Remarks

This paper aimed at developing the concept of sustainable development in a systematic framework, with the purpose of providing an applicable and operational definition of sustainability. This attempt had the intention to try and satisfy today's needs for defining and evaluating sustainability policies.

For this purpose we tried to determine an operational and measurable criterion for sustainable development that would fit into a *non-optimizing economic framework*. We consider such a non-optimizing framework as adequately representing current economic structures. By considering two different approaches for choosing policy instruments, a *feedback rule* and an *arbitrary rule*, we determined two criteria for sustainable development which could be applicable and measurable in applied work. In particular we considered economies, where domestic population growth, migration, labour augmenting technical change, environmental damages associated with pollutant flows generated by economic activities are taken into account in determining the sustainability conditions.

The developed sustainability criteria were further applied to the case of the Greek economy and empirical estimates were obtained. Our findings confirmed that our theoretical framework can be used for empirical purposes. In particular our results show that migration inflows, exogenous technical change, growth of capital per worker and SO<sub>2</sub> emissions are important factors characterizing the sustainability conditions for the Greek economy. Our approach allows to estimate the contributions of these factors in the achievement of a sustainable path, information which is undoubtedly useful for the design and evaluation of sustainable development policies. The main empirical finding is that although the Greek economy seems to be firmly on a sustainable development path if no environmental considerations are taken into account, considering such damages has undoubtedly negative effects on the sustainability conditions. If marginal damages due to emissions are sufficiently high then the economy is not on a sustainable path. Thus our empirical results for the case of Greece come to reinforce the perception that pollution - in this case SO<sub>2</sub> emissions - is an important factor which affects

natural environment and consequently the sustainability conditions of the economy. A more precise quantification of these effects, is an open research area.

Admittedly sustainable development as a general definition, does not provide a systematic framework for policy design. The present paper is an attempt to make the definition operational and capable of providing empirical estimates of sustainability conditions with a firm foundation on the structure of the economy. Thus important fundamentals, such as the elasticity of the production function, the rate of technical change, migration, environmental damages, assets' rates of growth, play a key role in estimating sustainability conditions. The model developed in this paper can be extended and become more realistic, by including transition equations for stocks of pollutants, or natural resources (depletable or renewable) human capital, or uncertainty in the evolution of the economy. These extensions will provide better insights regarding the sustainability conditions of economies and our ability to provide meaningful estimates of these conditions.

## 7 Appendix

The Bernoulli equation is solved in the following way: Multiplying with  $\hat{k}_t^{-a}$  we have:

$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (\eta + \delta + m + g) \hat{k}_t \hat{k}_t^{-a} = s \hat{k}_t^{-a} \hat{k}_t^a \quad (50)$$

$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (\eta + \delta + m + g) \hat{k}_t^{1-a} = s \quad (51)$$

If  $\gamma = \hat{k}_t^{1-a}$  and  $\dot{\gamma} = \dot{\hat{k}}_t \hat{k}_t^{-a}$ , then we have:

$$\dot{\gamma} + (\eta + \delta + m + g) \gamma(1 - a) = (1 - a)s, \text{ which is linear in } \gamma \quad (52)$$

and the solution is the following:

$$\gamma_t = \left( \gamma_o - \frac{s}{\eta + \delta + m + g} \right) e^{-(1-a)(\eta+\delta+m+g)t} + \frac{s}{\eta + \delta + m + g} \quad (53)$$

replacing  $\gamma_t = \hat{k}_t^{1-a}$ , we have:

$$\hat{k}_t = \left[ \left( \hat{k}_o^{1-a} - \frac{s}{\eta + \delta + m + g} \right) e^{-(1-a)(\eta+\delta+m+g)t} + \frac{s}{\eta + \delta + m + g} \right]^{\frac{1}{1-a}}$$

$$\hat{k}_\tau = \left[ \left( \hat{k}_t^{1-a} - \frac{s}{\eta + \delta + m + g} \right) e^{-(1-a)(\eta+\delta+m+g)(\tau-t)} + \frac{s}{\eta + \delta + m + g} \right]^{\frac{1}{1-a}}$$

Following the procedure above and by using instead of  $\hat{y} = \hat{k}^a$  which is the typical Cobb-Douglas production function,  $\hat{y} = (1 - z_{\bar{P}}) \hat{k}^a$  the accumulation of capital in per effective worker terms becomes:

$$\dot{\hat{k}}_t = s(1 - z_{\bar{P}}) \hat{k}_t^a - (\eta + \delta + g) \hat{k}_t - m \hat{k}_t + z$$

Multiply with  $\hat{k}_t^{-a}$  we have:

$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (\eta + \delta + m + g) \hat{k}_t \hat{k}_t^{-a} = s(1 - z_{\bar{P}}) \hat{k}_t^{-a} \hat{k}_t^a \quad (54)$$



$$\dot{\hat{k}}_t \hat{k}_t^{-a} + (\eta + \delta + m + g) \hat{k}_t^{1-a} = s(1 - z_{\bar{P}}) \quad (55)$$

If  $\gamma = \hat{k}_t^{1-a}$  and  $\dot{\gamma} = \dot{\hat{k}}_t \hat{k}_t^{-a}$ , then we have:

$$\dot{\gamma} + (\eta + \delta + m + g) \gamma(1 - a) = (1 - a)s(1 - z_{\bar{P}}), \text{ which is linear in } \gamma \quad (56)$$

the solution is the following:

$$\gamma_t = \left( \gamma_o - \frac{s(1 - z_{\bar{P}})}{\eta + \delta + m + g} \right) e^{-(1-a)(\eta+\delta+m+g)t} + \frac{s(1 - z_{\bar{P}})}{\eta + \delta + m + g} \quad (57)$$

replacing  $\gamma_t = \hat{k}_t^{1-a}$ , we have:

$$\hat{k}_t = \left[ \left( \hat{k}_o^{1-a} - \frac{s(1 - z_{\bar{P}})}{\eta + \delta + m + g} \right) e^{-(1-a)(\eta+\delta+m+g)t} + \frac{s(1 - z_{\bar{P}})}{\eta + \delta + m + g} \right]^{\frac{1}{1-a}}$$

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