Greenhouse gas emissions and the energy system: are current trends sustainable?

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Abstract

This paper discusses to what extent the recent trends in energy consumption and production are compatible with the requirements of sustainable development. For this purpose, starting from a simple identity applied to the energy sector, we use the decomposition analysis to derive a few analytical requirements for the long-term sustainability of the energy system and examine whether they are satisfied on the basis of the currently available data. From the analysis conducted in the paper, it emerges that an Environmental Kuznets Curve in energy intensity and/or carbon intensity may be insufficient to satisfy the sustainability conditions identified in the paper. Moreover, using simple graphical analysis, we show that the decomposition approach and the EKC imply two different relationships between per capita income (y) and carbon intensity (g_y) and discuss the relative implications.

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1. Introduction

The current system of energy production, distribution and consumption (henceforth energy system) is largely based on the use of fossil fuels that account for more than 80% of the world energy supply (IEA, 2008). The use of these resources, however, raises several serious problems because of polluting emissions, resource scarcity and concentration of their supply.

As to the first problem, fossil fuels generate greenhouse gases (from now on GHGs) that cause global warming by increasing the amount of infrared radiation (heat energy) trapped in it. The concentration of carbon dioxide (CO_2) in the atmosphere is currently estimated (IPCC, 2007) to be about 379 parts per million (ppm), a value much higher than before the Industrial Revolution (280 ppm. on average in the period 1750-1850). The IPCC (2007) estimates that the current level of concentration has already brought about an increase of 0.7 Celsius degrees in the average world temperature and if GHGs keep on growing at the present rate their concentration could double that of the pre-industrial period in the next few decades.

As to the second issue, fossil fuels are non-renewable energy sources. Therefore, although increasingly sophisticated methods of prospecting have allowed to find more and more reserves of fossil fuels over time, their overall amount is strictly limited. Experts, however, are currently divided on the size of these limits (cf. Porter, 2006, and the literature there cited), and it is very difficult to predict the timing and economic consequences of their exhaustion process.

Finally, fossil fuels are very concentrated in a few regions of the world, thus creating strong tensions for the economic and political control of these areas.[1] This makes the energy system rather vulnerable from the security viewpoint being highly dependent on the economic and political events occurring in these regions. Moreover, the remarkable concentration of oil and gas in terms of location and ownership makes predictions on the effective availability of their resources particularly difficult and unreliable.

For all these reasons, the current energy model has to face significant problems in terms of global warming, resource availability and security of supply that might endanger the continuation of the world economic development. This raises the question of whether and to what extent the recent trends in the energy system are compatible with the requirements of sustainable development. To investigate this question, in this paper we will limit our analysis to the first of the three issues mentioned above, the global warming problem, and examine the driving forces underlying the intertemporal evolution of the energy-related GHGs.

There exists a wide literature on the relationship between the energy system and GHG emissions. This paper builds on two broad research lines of this literature: the decomposition analysis and the Environmental Kuznets Curve (EKC) analysis. The former literature decomposes the change of an energy-related environmental indicator into its constituent parts in order to assess the contribution of the factors that influence such a change and analyze their evolution across different regions and over time (see Ang and Zhang, 2000, for a survey of these studies). The EKC literature empirically examines the relationship between environmental degradation and per capita income. Following a few pioneering contributions (Shafik, 1994; Selden and Song, 1994; Grossman and Krueger, 1995), these studies have been extended to the energy sector to test whether alternative energy measures of environmental degradation (in terms of polluting emissions or energy consumption) first increase and then decrease as per capita income rises (see Dinda, 2004, for a survey of the EKC literature).

This paper differs from the previous literature in two main respects. In the first place, differently from previous literature on decomposition analysis, the decomposition approach is used here to derive a simple sustainability condition and evaluate whether the current energy system has met this condition in the past and can do it in the future. As it is well known, sustainable development as originally suggested by the Brundtland Commission (WCED, 1987) is a very broad concept that may be consistent with several interpretations (see, e.g., Arrow et al., 2004). To avoid possible ambiguities, in the present work with this term we will mean development that does not increase GHG emissions, what will be defined for ease of reference as “GHG-sustainability”. We are fully aware that this indicative, hypothetical sustainability criterion *per se* is insufficient to stop global warming (as pointed out below). Most governments, however, are currently far even from satisfying this basic requirement, therefore the latter could be considered as an important first step to deal with climate change problems. Moreover, it provides a useful benchmark that allows to compare the simple stabilization of GHG emissions with more stringent reduction requirements such as those set by the Kyoto Protocol. In this sense, the GHG-sustainability criterion adopted here, provides a general framework of analysis that can be easily extended to investigate more demanding requirements.

In the second place, the present work differs from the previous literature since it jointly considers the decomposition and the EKC analyses, building a bridge between the two fields mentioned above.[2] More precisely, the decomposition approach is used in the paper to show that the EKC in energy intensity and carbon emissions intensity is not sufficient to satisfy the sustainability criterion adopted here. Moreover, using simple graphical analysis, we show that the decomposition approach and the EKC imply two different relationships between per capita income and carbon emissions intensity and use this observation to clarify the link between two alternative emissions indicators that are often used in the EKC literature (carbon intensity and per capita emissions).

The structure of the paper is as follows. Section 2 investigates whether the current energy trends are consistent with sustainable development as defined above, and show that the GHG-sustainability conditions derived from the decomposition approach are very demanding given the current energy trends. Section 3 uses the decomposition approach to explore whether the more optimistic outlook descending from the environmental Kuznets curve applied to the energy sector may be considered sound and convincing and show that, even if we accept the questionable assertion that such a curve exists, this does not necessarily imply that the sustainability conditions will eventually be met. Section 4 concludes.

2. The current energy system, global warming and the sustainability gap

In this section we intend to discuss to what extent the current trends of energy production and consumption are compatible with sustainable development, in the sense previously specified of non-increasing GHG emissions. For this purpose, in what follows we will adopt and extend the IPAT relation originally proposed by Holdren and Ehrlich (1974) to evaluate the environmental impact (I) of population (P), affluence (A, measured by per capita income) and technology (T, measured by environmental impact per unit of income).[3]

The IPAT framework has been subsequently applied to study the dynamics of carbon dioxide (CO_2) emissions through the so-called “Kaya identity”, from the name of the Japanese scholar who first reformulated the IPAT relation in terms of CO_2 energy-based emissions (Kaya, 1990). The basic idea of this approach is that of specifying one or more identities that indicate in quantitative terms the specific contribution of the main factors underlying the GHG emissions in order to analyze the global warming process and the policy strategy meant to mitigate its consequences. The analysis of the time evolution of these factors and their relative weights is useful from the descriptive, explanatory and predictive point of view as well as to clarify the policy choices that may bring about the best available scenario. The decomposition approach has been mainly used so far to give quantitative foundations to scenario analysis (see, for instance, IPCC, 2000) or perform regional analysis of the driving forces underlying the emission trends (e.g. Casler and Rose, 1998; Greening, 2004; Raupach *et al.*, 2007). Differently from that literature, in this paper we will use it to clarify a few crucial conditions of sustainability in order to evaluate to what extent the energy system complied with these conditions in the past and is going to deviate from them in the next decades. For this purpose, we will first consider the case of constant GHG emissions and then compare it with the more stringent GHGs reduction requirements set by the Kyoto Protocol.

We start the analysis by decomposing the impact on GHG emissions of a few crucial socio-economic determinants using the following identity:

$$(1) \qquad G = Pyefg$$

where G stands for the emissions of GHGs; P is the population; $y = Y/P$ is per capita income; Y is the GDP; $e = E/Y$ is energy intensity, namely, energy consumption (E) per unit of GDP; $f = F/E$ is the share of fossil fuels (F) on energy consumption and $g = G/F$ is the intensity of GHG emissions per unit of fossil fuel consumed.

Identity (1) may be interpreted as a specific application of the IPAT relation. In the present case, the environmental impact is measured by GHG emissions that are considered as the main anthropogenic cause of global warming; affluence is measured in terms of per capita GDP (y), while energy intensity (e), GHG intensity (g) and the share of fossil fuels (f) can be interpreted as proxies for the technological factor.

Taking the time derivative of the logarithms of the variables, we obtain an identity that connects additively the growth rates of the variables (indicated with an asterisk):

$$(2) \qquad G^* = P^* + y^* + e^* + f^* + g^*$$

From (2) we derive the following GHG-sustainability condition, namely, the condition that the growth rate of per capita income should satisfy to be consistent with a non-increasing path of GHG emissions ($G^* \leq 0$):

$$(3) \qquad y^* \leq -(P^* + e^* + f^* + g^*)$$

This approach can also be used to define an income sustainability gap that measures how distant the income growth rates are from a given environmental target chosen by the policy-maker. Let us assume, for instance, that policy-makers aim at keeping the current emissions level constant over time, i.e. $G^* = 0$. Replacing $G^* = 0$ in identity (2) and solving with respect to y^* we obtain the per capita income growth rate corresponding to constant GHG emissions. We indicate it with y^*_{max} since it is also the maximum growth rate of per capita income that complies with the GHG-sustainability requirement:[4]

(4) $y^*_{max} = -(P^* + e^* + g^* + f^*)$

We may then define the emissions growth rate G^* as the difference between the actual growth rate of per capita income and its maximum sustainable value, what we can define as the income sustainability gap:

(5) $G^* = y^* - y^*_{max} = y^* + (P^* + e^* + g^* + f^*)$

On the basis of these identities, it is possible to analyze what has happened in the world over the last three decades of the previous century and the forecasts of the Energy Information Administration (EIA) for the first three decades of the new century (EIA, 2008). The basic data are summarized in table 1 that reports the growth rates of GHG emissions (G^*) and of its constituent parts. The growth rate G^* is measured in the table, as a first approximation, with that of CO_2 emissions since the latter is generally used as a reference parameter for the aggregation of the other greenhouse gases, often measured in gigatons of CO_2 emissions equivalent (henceforth $GtCO_2$.e). In fact, though CO_2 is just one of the many GHGs that contribute to climate change,[5] it corresponds to 61% of the total GHGs emissions (IEA, 2008) and has a particularly long estimated atmospheric lifetime (50 to 200 years) so that it is considered as the main cause of global warming.

The last row in table 1 reports the expected growth rates of all the relevant variables for the period 2005-2030 based on the projections of the “Reference case scenario” (assuming current laws and policies unchanged throughout the projection period) provided by the EIA (2008). Although many institutions provide forecasts for different periods on single variables appearing in table 1, the EIA is the only source that computes estimations for all the variables here taken into account, thus ensuring a uniform estimation method.[6]

World	**G***	**Y***	**P***	**y***	**E***	**e***	**F***	**g***	**f***
1971-1980	2,8	4,1	1,9	2,2	3,0	-1,1	2,6	0,2	-0,4
1981-1990	1,6	3,2	1,9	1,3	2,1	-1,1	1,7	-0,1	-0,4
1991-2000	1,4	3,4	1,6	1,8	1,6	-1,8	1,2	0,2	-0,4
1971-2000	1,8	3,3	1,7	1,6	2,1	-1,2	1,8	0	-0,3
2005-2030	1,7	4,0	1,0	3,0	1,6	-2,4	1,6	-0.1	0.1

Table 1: EIA scenario.

Source: authors' elaboration on EIA (2008), British Petroleum (2008) and IEA (2008) data

Legend: G = CO_2 emissions, Y = income, P = population, y = per capita income, E = primary energy demand, $e = E/Y$ = energy intensity, F = total consumption of fossil fuels, $g = G/F$ = CO_2 intensity per unit of fossil fuel, $f = F/E$ = share of fossil fuels on energy consumption. The star above each variable indicates the growth rate of the variable.

As table 1 shows, the growth rate of CO_2 emissions G^* has always been strictly positive over the last three decades of the previous century, so that the estimated trends do not comply with the requirements of GHG-sustainability. Nevertheless, as it emerges from the table, the trends have been gradually improving over the last three decades of the 20th century, mainly as a result of technological progress that reduced the global energy demand (E) and intensity (e). In particular, energy intensity e has fallen more and more rapidly from 1.1% in the 1970s and 1980s to 1.8% in the 1990s and is expected to decrease even further to 2.4% in the period 2005-2030. This was the result of greater attention being paid to energy-saving following the oil shocks of the 1970s which was then consolidated by increasingly rigorous energy policies in the '80s and '90s. Above all in the 1990s, a significant contribution to this virtuous trend was provided by the systematic introduction of information and communication technologies.

Despite this decreasing trend in energy intensity and the expected reduction in the demographic growth rate P^* (see table 1, column 4), available forecasts suggest that in the next decades CO_2 emissions might increase at a growth rate (+1.7%) that is almost the same as the one observed in the last three decades of the previous century and actually higher than that of the 1980s and 1990s, thus basically stopping the progressive reduction in their growth rate observed in the past. This is largely due to the expected increase in the per capita income growth rate y^*, but also to the incapacity of achieving significant improvements in g and f. The GHG intensity g is destined to remain almost unchanged (-0.1%) over the next three decades, basically repeating the average performance of the past decades, while the share of fossil fuels f, which had slightly fallen in the past, is expected to revert its trend and grow in the future, although at a very low rate (0.1%).

The EIA projections discussed above clearly depend on the underlying assumptions and calculation methods. Therefore, using version 6.0 of the Climate Analysis Indicators Tool (CAIT) of the World Resources Institute (2009), we also compared forecasts on the future trend of global GHG emissions over the same period (2005-2030) derived from a variety of models used from different institutions (table 2).

Source	**G***
EIA-Reference	1,7
EIA-High	2,1
EIA-Low	1,3
IEA-Reference	1,6
POLES	2,2
SRES A1	2,2
SRES A2	2,3
SRES B1	1,6
SRES B2	1,3
SRES A1F1	2,6
SRES A1T	2

Table 2: expected average annual growth rate of CO_2 emissions in the period 2005-2030.

Legend: EIA-Reference = EIA (2008) Reference case scenario; EIA-High = EIA (2008) High case scenario; EIA-Low = EIA (2008) Low case scenario; IEA-Reference = IEA (2008) Reference case scenario; POLES = Prospective Outlook on Long-Term Energy Systems (European Commission, 2003); SRES = Special Report on Emission Scenarios (IPCC, 2000).[7]

As the table shows, projections may differ substantially under alternative scenarios, the expected growth rate *G** ranging from 1.3% to 2.6% over the same period. However, no major differences occur at the global level under the Reference case scenario across different institutions (cf., for instance, EIA-Reference *versus* IEA-Reference projections). All the emission projections taken into account forecast that CO_2 emissions will keep on increasing in the next three decades, so that the estimated trends do not comply with the requirements of GHG-sustainability. Most available projections (9 out of 11) actually forecast that the growth rate of GHG emissions will accelerate with respect to the 1990s (when G* was around 1.4%). And even in the two most optimistic scenarios where this does not occur (the Low case scenario of EIA, 2008, and the SRES-B2 of the IPCC, 2000), the growth rate G* is expected to slow down very slightly with respect to the 1990s (from 1.4% to 1.3%) and remain well above zero.

This suggests that existing policies are inadequate not only to reach but also to approach the stabilization of current emissions. As mentioned above, moreover, this minimum target is by no means sufficient to stabilize the concentration of GHGs in the atmosphere since their current flow -around 44 gigatons of CO_2 emissions equivalent ($GtCO_2$.e) in the year 2000 (IEA, 2008)- is much higher than the flow that the biosphere is able to absorb (that it is estimated to be 5 $GtCO_2$.e per year). Because of the strong inertia inbuilt in the natural processes underlying global warming, it is calculated that, even if we succeeded in stabilizing the concentration of GHGs at year 2000 levels (reducing the emissions flow down to their natural absorption rate), the world average temperature would still increase by another 0.1°C per decade in the next twenty years (IPCC, 2007).

This problem is fully recognized by the Kyoto Protocol. As it is well known, the Protocol requires an average reduction of GHG emissions of 5,2% at the world level in the period 2008-2012 with respect to the 1990 level. Introducing the emissions target $G^* = -0.052$ in equation (2) and solving with respect to y^*, we obtain the maximum income level that is consistent with the Kyoto target which will obviously be 5.2% lower than the one consistent with the case of constant GHG emissions considered so far. This implies that the sustainability gap with respect to the Kyoto target would be about 5% higher than according to the baseline of zero emissions growth examined above, which further decreases the chance of stabilizing global warming even through a very determined policy strategy. Since in the meantime world CO_2 emissions increased by an additional 32% with respect to the 1990 level (EIA, 2008), to comply with the Kyoto targets the decrease of emissions in the last years of its application should be about 37%.[8] It is easy to conceive that the Kyoto objectives will not be easily obtained by most Annex I parties and that the next years will be characterized by intense negotiations about how to conceive the after-Kyoto global strategy against global warming. The current trends, however, are quite distant from this target.

Behind these negative trends there is an overly slow transition process towards an alternative model based on the massive use of renewable resources.[9] The International Energy Agency (IEA, 2004) forecasts that the percentage of world energy consumption met by all renewable sources will remain unchanged (around 14%) between 2002 and 2030.[10] Similarly, the total share of renewable energy sources in world electricity generation is expected to increase by only 1% (from 18% to 19%) in the same period. The explanation set forth for such a slow transition process is generally that energy produced from fossil fuels costs less and will continue to do so for the whole period. This explanation, however, seems only partly valid. Indeed, this affirmation is based on an unsatisfactory way of calculating the cost per kilowatt-hour that does not take into account the external costs that in the case of fossil fuels are particularly high. If such externalities were properly internalized, then the price gap between renewable and exhaustible resources would substantially decrease and the optimal timing for the transition towards renewable energy sources should probably be much anticipated.

3. The decomposition approach and the EKC

The GHG-sustainability conditions descending from the decomposition approach are very demanding for the current energy trends. A more optimistic point of view is often based on a questionable interpretation of the empirical evidence concerning the potential existence of an Environmental Kuznets Curve applied to the energy sector. Both CO_2 per capita emissions and CO_2 intensity (i.e. CO_2 emissions per unit of GDP) seem to follow a Kuznets-type path (Schmalensee et al. 1998, Galeotti and Lanza, 1999, Sachs et al., 1999). As Sun (1999) has pointed out, since the current energy model is heavily dependent on the use of fossil fuels, this seems to reflect the existence of similar bell-shaped curves in terms of per capita energy consumption (Schmalensee et al., 1998) and energy intensity (Suri and Chapman 1998; Focacci, 2003). The EKC that turns out in cross-country analyses, however, is the result of two opposite trends at the world level, ascending in developing countries and descending in developed ones (Roberts and Grimes, 1997). But the EKC tends to disappear when we pass from cross-country to single-country analysis (cf. de Bruyn et al., 1998; Roca and Serrano, 2007; Dijkgraaf and Vollebergh, 2005; Lantz and Feng, 2006). Therefore, nothing ensures that those countries that are currently on the growing portion of the curve will be able to reverse this trend and run along the desired declining part in the future. In many studies, moreover, the turning point of the estimated EKC falls well beyond the range of the observed income levels (Shafik 1994, Holtz-Eakin and Selden 1995, Cole et al. 1997), suggesting that CO_2 intensity and per capita emissions might continue to rise for a long time before reaching the downward part of the curve.

Finally, even if we accept, for the sake of the argument, the existence of an EKC in terms of CO_2 intensity and per capita emissions, this does not guarantee a similar bell-shaped curve for total emissions. However, it is the total amount of CO_2 emissions (rather than its ratio over total GDP or population) that matters to evaluate the impact of human activity on climate change. Total CO_2 emissions have been steadily increasing with per capita income in the last decades (see fig. 1). Though their growth has slowed down on average after the oil shocks of the 1970s, the evolution of CO_2 emissions does not show yet any sign of reversal in its long-run trend. Since per capita GDP also grows steadily over time, this seems to suggest that total CO_2 emissions do not follow an inverted-U shape even if we replace time with per capita income on the horizontal axis.

In other words, the possible existence -at least in cross-country analyses- of an EKC in terms of CO_2 intensity (per capita CO_2) ensures only that total income (population) will grow faster than total CO_2 emissions beyond a given per capita income level. But this does not imply that total emissions will be decreasing. This point can easily be shown by using the decomposition approach developed in the previous section. Consider, for instance, equation (2). As the identity shows, an Environmental Kuznets Curve in energy intensity is not sufficient to achieve

GHG-sustainability. An EKC in energy intensity, in fact, can only ensure that e^* (but not G^*) would eventually become negative. However, the growth rate of CO_2 emissions also depends on the trends of income, population, emissions intensity and fossil fuels' share, as explained by identity (2), that can more than counterbalance the reduction in e.

The decomposition approach can also be used to explain why the EKC in carbon intensity is also insufficient to comply with GHG-sustainability. To fix ideas, let us consider the following elementary decomposition:

(7) $g_p = yg_y$

where g_p stands for G/P and g_y for G/Y. Notice that using this decomposition we can rewrite equation (2) as follows:[11]

(8) $G^* = P^* + y^* + g_y^*$

Repeating the same reasoning seen above, an EKC in carbon intensity g_y implies that g_y^* will eventually be negative while y^* is always positive along the curve, but it provides no indications on the sign of G^*.

Identity (7) can contribute to shed light on the different implications of the decomposition and the EKC approach for the carbon intensity path. Notice that in the case of identity (7), the relationship between g_y and y is expressed by a family of equilateral hyperbola parameterized by g_p (fig.2). We may wonder whether such a relationship between g_y and y is consistent with the very different one expressed by the EKC relating the same variables. The answer is positive because the EKC aims to capture an empirical regularity between g_y and y based either on cross-section or time-series analysis, while identity (7) makes explicit logical constraints that in any instant must be respected by the EKC. In other words, every point that lies on the EKC must also lie on one of the existing hyperbola.

The analysis of figure 2 may provide some interesting insights on the possible links between changes in carbon intensity g_y and changes in per capita emissions g_p. As the economy moves upward along the increasing portion of the EKC (from A to B to C), it also shifts towards higher values of per capita GHG emissions (from g^1_p to g^2_p to g^3_p) so that both variables (g_y and g_p) increase as per capita income rises. Suppose now that the economy reached point C (the peak of the EKC) and that we aim at reducing carbon intensity to a given threshold level k.[12] In order to achieve k, we can move either along the EKC (from C to D) or along the hyperbole g^3_p (from C to E). If we move along the EKC, per capita emissions g_p will first rise (from g^3_p to

g^4_p) and then fall (from g^4_p back to g^2_p) as per capita income y grows. Therefore, if carbon intensity g_y follows an EKC-path, also per capita emissions g_p will first go up and then down as income grows. In other words, if there exists an EKC in g_y, then also g_p will eventually delink from per capita income growth, but the curve in g_p reaches a peak at a higher per capita income level than that in g_y ($y_4 > y_3$).[13] If we move, instead, along the hyperbole, g_p will stay constant, while g_y diminishes as y increases, so that only the latter variable will manage to delink from per capita income growth.

Notice that both movements (along the EKC and along the hyperbole) imply a reduction of g_y. However, in the first case the relationship between g_y and y will be concave (describing a proper inverted-U EKC), while in the second case it will be convex. Therefore, if we move along the hyperbole rather than along the EKC, it could take much longer for the economy to achieve k; the more so, the lower is the given environmental target.

We have to conclude that, even if we accept the hypothesis that carbon intensity starts falling when per capita income gets sufficiently high, using the decomposition approach we can show that this reduction can occur in different ways and with different timing. Moreover, nothing ensures that an EKC in g_y will actually occur, whereas the decomposition approach describes a relationship between g_y and y that must necessarily hold at every instant of time. The decomposition approach, therefore, is a much more general, rigorous and flexible tool for analyzing the sustainability conditions than the EKC.

5. Concluding remarks

The current energy system has to face significant problems in terms of limited availability of fossil fuels, vulnerability of their supply and global warming generated by their use. Focusing attention on the latter issue, in this paper we have examined the sustainability of the current energy system relating two alternative approaches that have been adopted in the literature so far: the decomposition analysis and the EKC analysis.

The findings of the EKC literature may induce some optimism on the capacity of economic systems to solve in the long run the climate change problems that we observe today. In fact, many studies support the existence of an EKC in emissions intensity and carbon intensity so that the latter variables will eventually fall as per capita income grows. As Tol *et al.* (2009, p.3) have argued, however, this process might be “not sufficiently fast to meet the targets of climate policy”. More precisely, as we have shown above, an EKC in energy and carbon intensity (provided it exists) is not sufficient per se to ensure a decrease in the total amount of GHG emissions generated by the current energy model.

The latter aspect can be easily proved by adopting a more general approach to the analysis of the pollution-income relationship than the one generally pursued in the EKC literature. This approach, that is based on the decomposition of total GHG emissions in a few crucial socio-economic determinants, has been used in this paper to derive some basic sustainability conditions in terms of non increasing GHG emissions. Although the decomposition approach discussed here is certainly too simple to account for many important details of the interaction between socioeconomic processes and global warming, it provides a straightforward and intuitive way to examine whether these sustainability conditions have been and/or will be verified by the energy system.

The GHG-sustainability criterion adopted here is consistent with both constant and decreasing GHG emissions, therefore it should be regarded just as first step to face the serious challenges posed by global warming. Keeping GHG emissions at their current level would be insufficient to stop global warming, and only a steady reduction of GHG emissions over time would allow to bring emissions below the natural absorption capacity. From the analysis of the available data, however, it emerges that the world economic system has been unable so far even to stop the growth of GHG emissions and all available projections forecast that such emissions will keep on growing in the next few decades. This depends mainly upon an overly slow transition process towards a new way of producing, distributing and consuming energy based on the use of renewable sources. This stance may widen even further the sustainability gap (namely, the distance from the sustainability target) which has characterized the last decades, as confirmed by the recent EIA estimates. While the sustainability gap has been positive but declining over the last decades of the previous century, it could rise again in the future if the policy strategy is not going to change. As it emerges from the decomposition analysis conducted in the paper, several factors contribute to this trend. In particular, the share f of fossil fuels on energy consumption is expected to slightly increase in the future, thus inverting its declining trend observed in the last decades. On the contrary, the reduction in f should be strengthened to increase the share of alternative renewable resources. Moreover, according to current projections GHG intensity g is likely to remain almost constant in the next decades. The obvious way to reduce it relies on a systematic shift towards fossil fuels with a lower carbon content (from coal to oil to natural gas). However, this process of substitution could be checked by a few serious obstacles. Coal, in fact, is characterized by more diversified markets and lower transportation and distribution costs than the other fossil fuels. Moreover, cheaply accessible coal reserves are much greater than those of oil and natural gas. In particular, many important countries such as India and China have very limited reserves of oil and natural gas and huge reserves of coal so that the substitution of the latter with less polluting fossil fuels could run against their economic and security targets. In this situation, if the scarcity of oil or gas will become binding in the next decades, this might shift the energy system towards increasing use of coal rather than alternative cleaner non-fossil sources of energy, which would move the world economic system further apart from the basic sustainability requirements examined in this paper. To avoid this risk it would be important to adopt a far-sighted policy strategy that promotes energy-saving and renewable sources, thus allowing a smooth transition towards a different and more sustainable energy system in the future.

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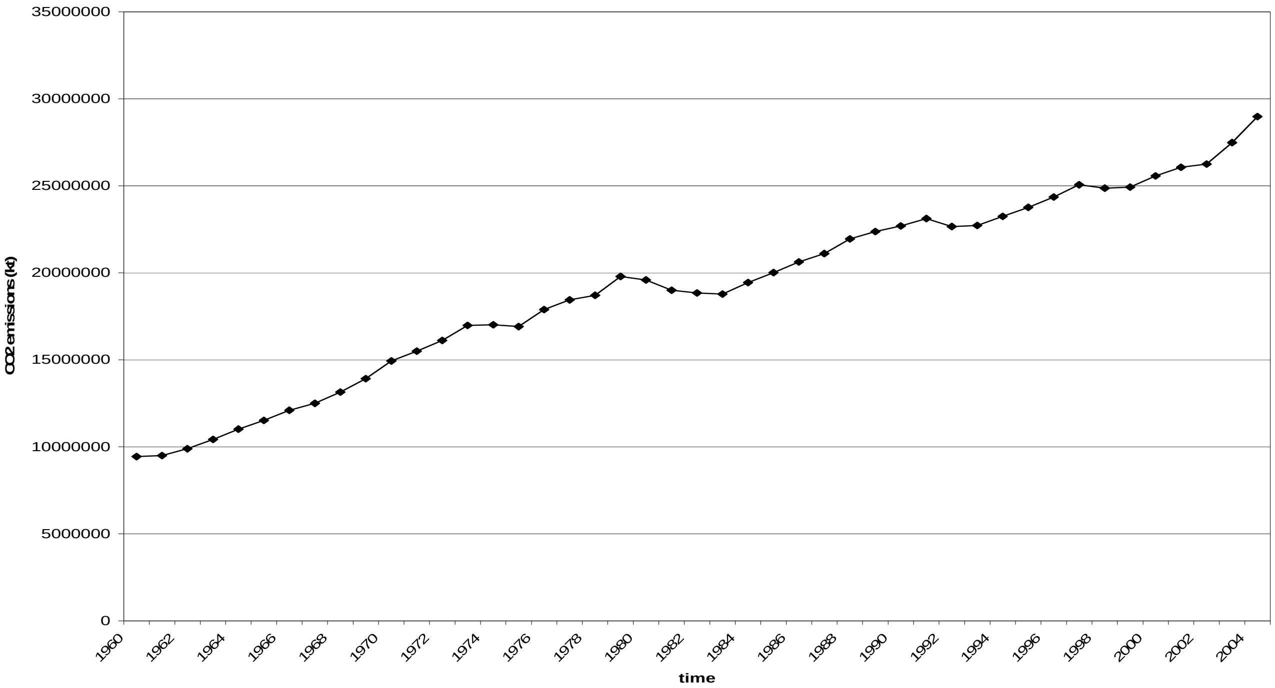

Figure 1: total CO_2 world emissions, 1960-2004.

Source: *authors' elaboration on World Bank, World Development Indicators (2008)*

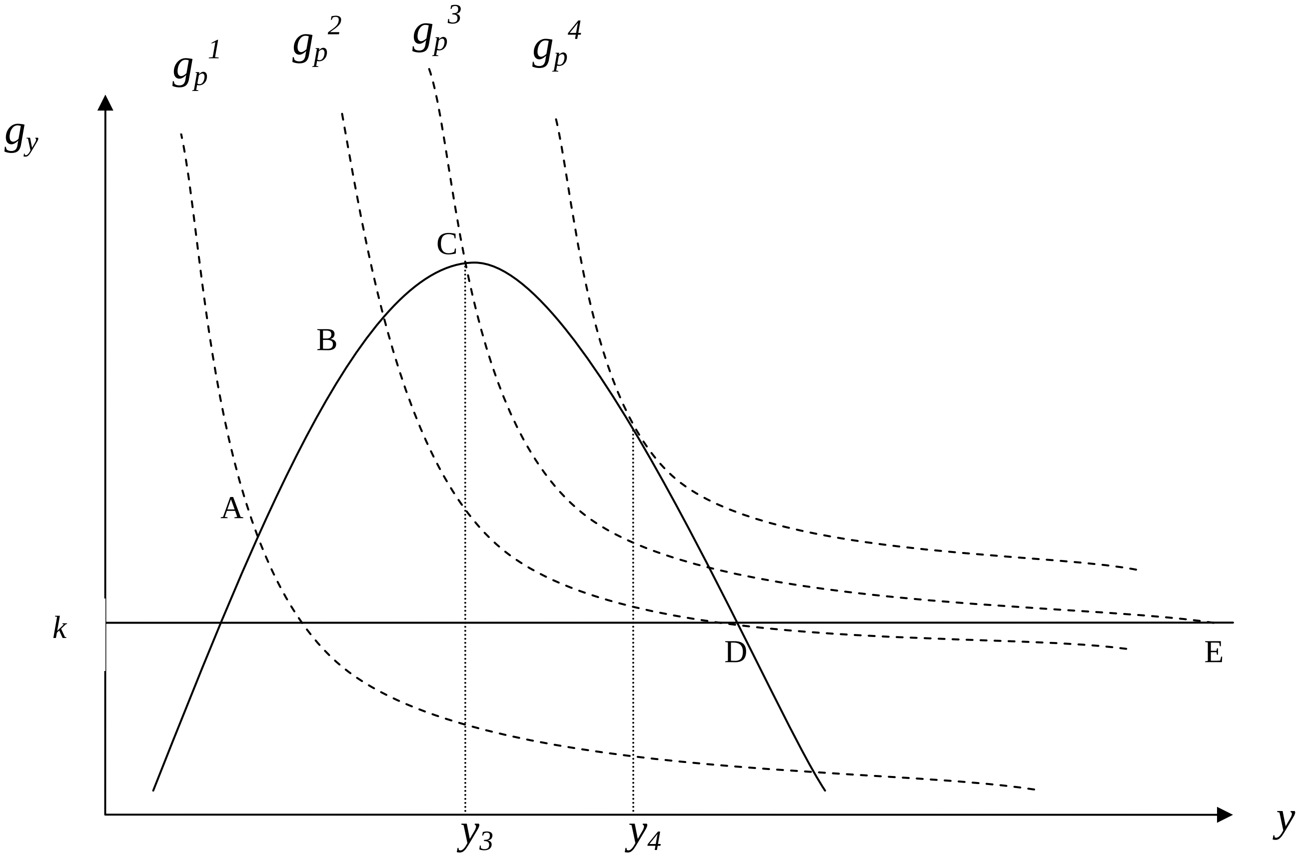

Figure 2: diagram of identity (7) (dotted lines) and of the EKC in g_y (continuous line)

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[1] More than 60% of the world's oil production is concentrated in only five countries (Saudi Arabia, the United Arab Emirates, Iraq, Kuwait and Iran). If we exclude the North Sea and the USA, the remaining percentage is mainly concentrated in areas of high tension and political instability such as, for example, the west coast of Africa, Libya, Algeria, Russia and the post-Soviet Caspian republics. Similarly, 56% of the world's gas reserves are concentrated in just three countries: Russia, Iran and Qatar (IEA, 2008).

[2] Only a few works have looked at both literatures so far using decomposition analysis to empirically investigate the origins of changes in emissions level and their relationship with economic growth (de Bruyn, 1997; Bruvoll and Medin, 2003; Lantz and Feng, 2006; Roca and Serrano, 2007; Tol et al., 2009). Differently from these contributions, we will provide a few theoretical insights on the link between decomposition analysis and the EKC that hold true independently of specific parameter estimations.

[3] See Waggoner and Ausubel, (2002) for a renovated use of the IPAT identity that identifies the economic actors with the forces driving the environmental impact.

[4] The maximum sustainable growth rate will obviously be equal to $y^*_{max} - x$ if the policy maker aims at reducing GHG emissions by a given percentage x. This can be easily obtained by replacing the target $G^* = -x$ (instead of $G^* = 0$) in (2) and solving with respect to y^*.

[5] See IPCC (2001) for an exhaustive classification of the numerous GHGs, their lifetime and their global warming potential expressed in terms of CO_2.

[6] The growth rates of fossil fuels' consumption F^* (and consequently also the last two columns g^* and f^* in table 1) have been computed integrating the EIA data with those provided by British Petroleum (2008) and IEA (2008). More precisely, F^* is equal to the average of the growth rates of oil, coal and natural gas (provided by EIA, 2008) weighted by the share of total consumption F satisfied by each fossil fuel (computed using the datasets of British Petroleum, 2008, and IEA, 2008).

[7] IPCC Scenarios: A1 = very rapid economic growth, global population peaks in mid-century and declines thereafter, rapid introduction of new and more efficient technologies; A2 = continuously increasing population, per capita economic growth and technological change more fragmented and slower than in other scenarios; B1 = global population peaks in mid-century and declines thereafter, reductions in material intensity and introduction of clean and resource efficient technologies; B2 = continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines; A1F1 = as A1 with fossil intensive technological improvements; A1T = as A1 with technological improvements mainly in non-fossil energy sources. All projections start from year 2005 a part from those of the IEA that start from 2006. See World Resources Institute (2009) for a detailed description of all models and scenarios.

[8] The emissions abatement requirement would actually be even higher if we took into account the increase in the other GHGs (different from CO_2) that occurred since 1990.

[9] See Smil (2006) for an historical perspective on the pace of the coming conversion to an alternative energy system as compared to previous energy transitions.

[10] Notice that if we exclude biomass, the other renewable sources (i.e. hydropower, solar, geothermal, wind, tidal and wave energy) will account for only around 4% of global energy demand in 2030 (IEA, 2004).

[11] Observe that it is: $g_y = efg$. Differently from g, that measures GHG intensity per unit of fossil fuels consumed, the variable g_y measures GHG intensity per unit of GDP. Since GHG emissions are here measured in terms of CO_2, for the sake of simplicity in what follows we will refer to g_y as carbon intensity.

[12] The latter could be given, for instance, by the ratio between the natural absorption of GHG emissions and total income. In this case, reducing g_y below k would also reduce total emissions below the absorption capacity of the atmosphere, thus satisfying one of the most frequently used notions of sustainability in terms of pollution (Ekins, 1992).

[13] See Borghesi and Vercelli (2008) for an analytical proof of this result with explicit functional forms.