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Energy, Development, and the Environment: An Appraisal Three Decades After the "Limits to Growth" Debate

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Energy, Development and the Environment: An Appraisal three Decades After the "Limits to growth" debate [*]

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Abstract

This work builds upon some long-term secular regularities concerning the relation between consumption of energy, technological progress and economic growth and reassesses the old question raised around forty years ago in the "limits to growth" discussion (Meadows et al. [1972]), namely are the current patterns of development and in particular the current patterns of energy use environmentally sustainable?

The questions we shall address are the following. First, the environmental sustainability of patterns of energy consumption that for long have implied the notion of the environment as a free good, without any negative social externalities and even less so any environmental threat. Second, the importance - and limits - of relative price changes with respect to the dynamics of consumption of energy. Third, the role of fundamental discontinuities between different "technological paradigms".

Keywords:
Energy Consumption, Emissions, Sustainability

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1 Introduction

This work builds upon some long-term secular regularities concerning the relation between consumption of energy, technological progress and economic growth and reassesses the old question raised around forty years ago in the “limits to growth” discussion (Meadows et al. [1972]), namely are the current patterns of development and in particular the current patterns of energy use environmentally sustainable?

Without the ambition to offer any conclusive answer, in this work we try to identify some critical interpretative issues and suggest some (admittedly controversial) policy conclusions.

Departing points are: (a) the long-term substitution of inanimate sources of energy for animate, starting at least with English Industrial Revolution, (b) a slowly decreasing - on a shorter time scale - trend of energy intensity per unit of output, at least in developed countries, as the joint outcome of total energy consumption which continues to increase (IEA [2005]) and at the same time more efficient exploitation of energy itself, (Grüber and Nakićenović [1996] and Fig. 3 below).

The questions we shall address are the following:

First, the environmental sustainability of patterns of energy consumption that for long have implied the notion of the environment as a free good, without any negative social externalities and even less so any environmental threat.

Second, the importance - and limits - of relative price changes with respect to the dynamics of consumption of energy.

Third, the role of fundamental discontinuities between different “technological paradigms”.

Given the observed trends we propose some interpretative and normative conjectures:

First, the proposition that “growth takes care of itself” in term of the environmental consequences is analytically largely ungrounded and normatively reckless.

Second, the higher the price for fossil fuels, the better it is in the long run for the world economy as for humankind in general.

Third, even sky-rocketing prices of fossil fuels alone might not be enough to endogenously induce a sustainable pattern of consumption.

Major research projects involving also massive public investments in basic research are needed if we want to maintain (or re-gain?) long-term environmental sustainability.

2 The long term patterns of energy consumption and their sustainability

Let us begin with the patterns identified by Landes [1969] who provides a careful history of diffusion of various energy sources during and after the Industrial Revolution.

Before the 18*th* century the only non-animal source of chemical work was heat from charcoal-fired furnaces. Coal had entirely replaced char-coal in England before 1800 due to prior deforestation. In the U.S. the process took longer. Inanimate sources of work exceeded animal work in the U.S. for the first time in 1870. However it was not until the 20*th* century that the contribution of fossil fuel combustion and heat engines using fossil fuels overcame the contribution of biomass; and this has been only the case for industrialized countries, see Ayres [2004]. Figure 1 offers an appraisal of the trends in energy[1] consumption in U.S.

Somewhat surprisingly, as Fig. 1 shows, coal was able to maintain its leading position up until the mid 20th century, due also to its role in industrial production: indeed Fig. 2 shows that coal consumption still displays an increasing trend, with the sole exception of Germany.

Overall, as already mentioned, the secular post-industrial revolution trends display an exponential increase in *total* energy consumption notwithstanding a slowed down over the last half century or so due to a fall in the energy intensity per unit of GDP (at least above some level of GDP per capita): cfr. again Fig. 3 on the USA. With that go together also similar patterns in CO_2 emissions since the bulk of the increase in energy use has involved fossil fuels.

Are such patterns sustainable in the long-run?

As many recall, the first spur in such debate occurred in the early seventies around the "Club of Rome" manifesto in turn grounded in forecast of the simulation exercise by Forrester and colleagues at MIT (Meadows et al. [1972]).

Within that discussion the major emphasis was on the limit to growth related to *resource availability* coupled with rapid population growth and after 1973, by the rising trend in oil prices and declining growth in output in many industrialized countries (see also Nordhaus [1992]).

Those who stood on the pessimists' side, argued that on the basis of the MIT models, disaster could be avoided only by zero population growth and zero economic growth from year 2000 on. Optimists - which at the time included Chris

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[1] The term energy as used in everyday discussion - economics included - is technically incorrect (see, Ayres et al. [2003]) as it means conserved quantity. Therefore, it cannot be "used up" but only converted from available to unavailable forms. The correct term in this context is *exergy*, which is roughly speaking, "available energy" or "potentially useful" energy. Having said that we conform to the existing terminology adopted in economics and we reiterate the misuse of the word *energy consumption.*

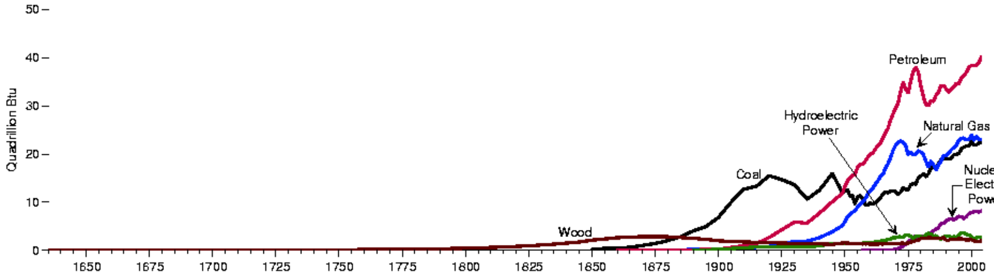

Figure 1: Energy Consumption by Source, 1635-2004 Source DOE/EIA [2004]

Freeman and collaborators at the Science Policy Research Unit at Sussex - argued that growth could continue, provided that the two following conditions were to be met: (a) a combination of institutional changes that led to different path of world development (with more emphasis on sustainability) and (b) a re-orientation of world R&D so that environmental objectives could be given higher priority (see Freeman [1992]).

The scenario drawn by the Club of Rome turned out be *overpessimistic* in assessing the importance of natural resources shortage in constraining economic growth. At the same time the scenario was heavily *optimistically* biased in relation to the environmental impact of pollutant emissions into the environment in general and the impact of energy use on climate in particular. As Brock and Taylor [2004] vividly put it: “Recently it has become clear that limits to growth may not only arise from nature’s finite source of raw materials, but instead from nature’s limited ability to act as a sink for human wastes.” A much more reasonable setting to assess the interactions of human activities and the ecosystem is to frame it in terms of the twofold role of *source and sink* played by the environment, with the sink role and its long-term effect in the forefront. In fact, in our view the Club of Rome warnings massively underestimated the powers of technological progress with respect to the access to/ exploitation of natural resources. Knowledge accumulation has made wonders in disproving dismal predictions dating back in economics at least to Ricardo and Malthus. Contrary to the Ricardian intuition on scarce factors of production very little by ways of decreasing returns to resources availability (including energy) have played out over the last two centuries. Rather technology-driven dynamic increasing returns exerted their powerful influence also in agricultural, mining and energy extraction.

Conversely the crucial long-term sustainability issue regards, we suggest, the compatibility between current patterns of resources use - and in particular energy use - and environmental dynamics. The latter include, of course, greenhouse effects by now abundantly documented. Hence, even granted the ability of nature to

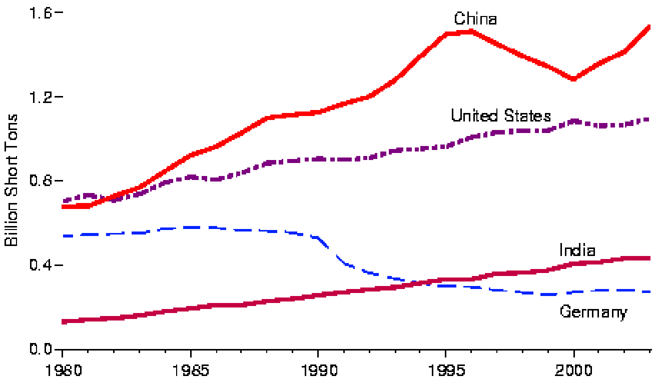

Figure 2: World Coal Consumption, 1950-2004 Source DOE/EIA [2004]

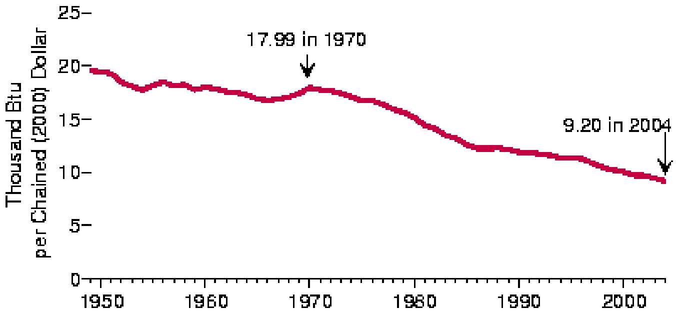

Figure 3: Energy Use per Dollar of GDP Source DOE/EIA [2004]

partly fulfill its “sink role” what are the limits of its recycling capacity? And on the other side what is the relationship between rates of environmental waste and development?

Environmental Kuznets Curves

The statistical features of the relationship between energy consumption and levels of development are often summarized by means of the so-called “Kuznets curve”

As Dasgupta et al. [2002] put it (p. 147):

> “The Environmental Kuznets Curve (EKC) posits an inverted-U relationship between pollution and economic developments. Kuznets name was apparently attached to the curve by Grossman and Krueger [1994], who noted its resemblance to Kuznets’s inverted-U relationship between income inequality and development.”

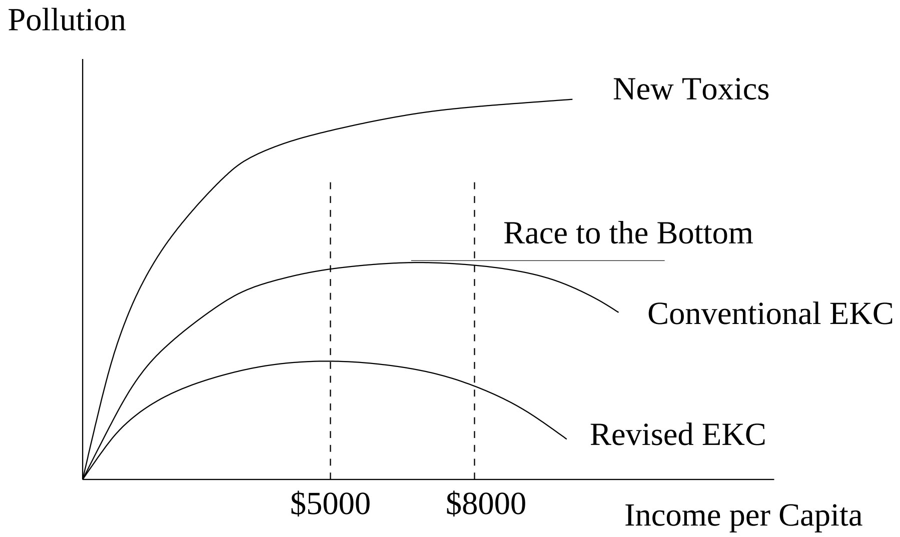

Figure 4: Environmental Kuznets Curve. Source Dasgupta et al. [2002]

Different versions of the EKC characterized by different degrees of optimism are illustrated in figure 4. Dasgupta et al. [2002] and Stern [2004b] offer two quite comprehensive reviews of the literature on the subject.

Their most optimistic interpretations have been popularized, not too surprisingly, by the World Bank's *World Development Report 1992* which argued that:

> The view that greater economic activity inevitably hurts the environment is based on static assumptions about technology, tastes and environmental investment (IBRD [1992], p. 38).

Should the EKC be verified the take-away message would be: Grow first, then clean up: i.e. the so-called "too poor to be green" hypothesis (Martinez-Alier [1995]).

Clearly, if supported by the data, the EKC, especially in its most optimistic versions (cf. the two lower curves in Fig. 4), would apparently suggest that, first, a path to environmental sustainable growth is available for developing countries, given existing techniques and, of course, that second, developed countries are already following it. Emerging economies would only need to "replicate" the growth path already set by more advanced economies.

The most robust evidence supporting EKC is for developed countries, as for these countries more data on emissions and longer time-series are available.

de Bruyn et al. [1998] spell out some possible drivers of EKC (at least for local air pollutants): *first*, one tends to observe positive income elasticities for environmental quality; *second*, structural change in production and consumption toward "good" environmental friendly directions tend to be associated with higher per capita income; *third*, information on environmental consequences of economic activities increases with income levels.

Granted that what is the evidence supporting the EKC, and what does it imply?

Some Statistical evidence on EKC

Let us consider the following basic "reduced form" model largely tested in the literature (de Bruyn et al. [1998], pp. 163 and 164):

$$E_{i,t} = \alpha_{i,t} + \beta_1 Y_{i,t} + \beta_2 Y_{i,t}^2 + \beta_3 Y_{i,t}^3 + \beta_4 t + \beta_5 V_{i,t} \tag{1}$$

where, E is "environmental pressure" (however defined), Y is per capita income, i stands for a country index, t is a time index, V_t reflects other variables that influences the relation between Y and E. Clearly the picture would be coherent with the traditional EKC for $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 = 0$.

The typical approach to test the EKC has been to regress cross-country measures of environmental and water qualities on various specifications of income per capita. Most of these studies rely on the Global Environmental Monitoring System (GEMS), sponsored by U.N., which collects data on pollution both in developed and developing countries.

Researchers are far from agreement on the empirical goodness of fit of an EKC type model. For example, according to Stern [1998] the evidence on a U-shaped relation only applies to some air pollutants such as suspended particulates and sulfur dioxide.

Bandyopadhyay and Shafik [1992] correlate ten types of environmental pressure with per capita income for a panel of up to 149 countries for various time intervals between 1960 and 1990. Only two types of environmental pressure, urban air concentrations of SPM and SO_2, follow an EKC according to their estimates. Emissions of CO_2, an indicator for water pollution and the amount of municipal solid waste per capita satisfy a monotonic, positive relation with per capita income.

Bertinelli and Strobl [2005] propose a semi-parametric approach to the EKC with the consequent advantage of allowing for higher flexibility in accounting for the relation between income per capita and some measure of pollution. They find *a linear relation, with pollution increasing with country wealth for low level of GDP/capita and becoming flat thereafter.* The only exception to linearity is for very high GDP/capita ratios, with the disclaimer that due to very few observations in the higher tail, the curve is poorly estimated[2].

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[2] They also note that a source of bias could be in the unit root of the time series for pollutant

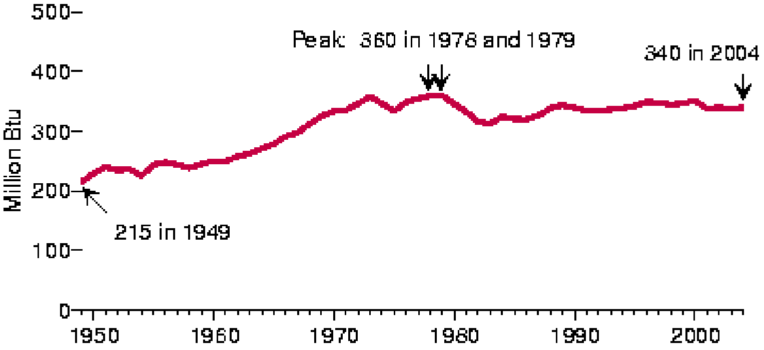

Figure 5: Energy Consumption Per Person, U.S.A. Source DOE/EIA [2004]

Stern [2004b] suggests that structural factors on both the input and output side do play a role in modifying the gross scale effect though they are mostly less influential than time-related effects. The income elasticities of emissions are likely to be less than one–but not negative in wealthy countries as proposed by EKC hypothesis. Further, the author also notice that most of the studies supporting the EKC might exaggerate any apparent decline in pollution intensity with rising income. Indeed, in our finite world the poor countries of today would be unable to find other countries from which to import resource-intensive products as they become richer. As a result, future research on this issue has to account also for the effects of pollution regulations on trade. With this respect Levinson and Taylor [2004] find - very reasonably - that those industries whose abatement costs increased most have seen the largest relative increases in net imports.

Moreover, thousands of potentially toxic materials remain untested and unregulated. Such an issue also affects the analysis of the effects of environmental regulation, both in developed and developing countries.

There is nearly a paradox here in that when the evidence of a damage is beyond any reasonable doubt it might be also when it is too late to revert the course of events. Further, some scholars suggest that even if some EKC relationship existed in the past, it is unlikely to persist in the future because of the pressures that global competition places on environmental regulations; the so called *race to the bottom* (Dasgupta et al. [2002][3]: see again Fig. 4).

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emissions. Thus, they proceed to first-difference the series. Nonetheless, their estimates for both sulfur and carbon dioxide emissions suggest that the relationship still appear to be linear.

[3] Moreover, the "new toxics" scenario claims that while some traditional pollutants might have an inverted U-shape curve, the new pollutants that are replacing them do not.

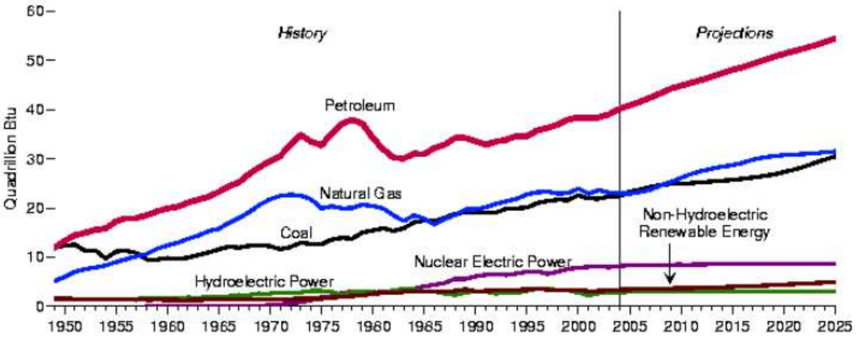

Figure 6: Energy Consumption by Source, History and Projections 1949-2025. Source DOE/EIA [2004]

Decomposing the determinants of energy use and environmental pressure

Given the highly controversial empirical evidence on EKC further insights might be drawn from dynamic frameworks explicitly disentangling the diverse underlying relations between growth, energy consumption and pollution[4].

Grossman [2005] and de Bruyn [1997] propose the following decomposition:

$$E_t = \sum_{j=1}^{n} Y_t I_{jt} S_{jt} \tag{2}$$

where E_t is emission in year t for a given country, Y is GDP, I_j is the emission intensity of sector j and S_j is the share of that sector in the country's economy. Such a representation allows to analyze emissions accounting for scale, (sectoral) composition and technique effects. Equation (2) is in fact an identity since $I_{jt} = E_{jt}/Y_{jt}$ and $S_{jt} = Y_{jt}/Y_t$ and can be used to distinguish various factors which influence on emissions. Differentiating both sides with respect to time we can write:

$$\hat{E} = \hat{Y} + \sum_{j=1}^{n} e_j \hat{S}_j + \sum_{j=1}^{n} e_j \hat{I}_j \tag{3}$$

where $e_j = E_j/E$ is the share of emissions of sector j in total emissions and $\hat{X} = [dX/dt]/X$.

The first term on the right hand side of equation (3), $\hat{Y}$, accounts for the effects on emissions directly related to scale, i.e. to the growth of the size of the

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[4] Needless to say, such a decomposition is only possible when detailed data about the economy and its sectoral composition are available for fuel use, output, emissions, etc.

	Weighted logarithmic percent change(%)
Total change	
Actual emissions	28.77
Predicted emissions	27.37
Unexplained fraction	1.40
Decomposition	
Scale effect	53.78
Emissions related technical change	-19.86
Energy Intensity	-10.20
Output mix	3.77
Input mix	-0.13

Table 1: Contributions to total change in global sulfur emissions. Source Stern [2002].

economy holding constant the composition of the economy and, broadly speaking, the technology as proxied by the intensity of emissions, while the two other terms on the right-hand side precisely account fo the latter[5].

Stern [2002] adopts a similar procedure to decompose sulfur emissions in 64 countries during 1979-1990:

$$\frac{S_{it}}{P_{it}} = \gamma_i \frac{Y_{it}}{P_{it}} A_t \frac{E_{it}}{Y_{it}} \prod_{j=1}^{n} \left(\frac{y_{it}}{Y_{it}} \right)^{\alpha_j} \sum_{k=1}^{K} \frac{e_{kit}}{E_{it}} \varepsilon_{it} \tag{4}$$

where S is sulfur emissions; P population; Y_{it}/P_{it} is scale as proxied by GDP-capita; A_t is a common global time effect representing emissions specific technical progress over years t; E_{it}/Y_{it} is energy intensity; $y_{1it}/Y_{it}, \ \ldots, \ y_{nit}/Y_{it}$ represent the composition effect and $e_{1it}/E_{it}, \ \ldots, \ e_{kit}/E_{it}$ is the input-mix given by the share of different energy sources e in total energy use E. Additionally, γ_i is the relative efficiency of country i compared to best practice, and ε_{it} is a random error term.

The results of the empirical analysis, which we report in Table 1 show that input and composition effects globally contributed very little, even though they might be important for certain countries. The two components accounting for technological change (A_t and E_{it}/Y_{it}) limit the increase in emissions to half, but are unable to prevent them from increasing.

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[5] Clearly, equation (3) requires a discretization for empirical applications.

Wing and Eckaus [2004] carefully review the existing empirical works and identify the following "stylized facts":

- Declining aggregate energy intensity (notwithstanding an *upward trend in its total use*);
- Evidence of induced energy-saving innovations at the micro level, associated with significant energy-saving technological change in a number of energy-intensive manufacturing industries;
- Indications of the embodiment of energy-saving innovations in durable goods;
- (Somewhat at odds with the evidence mentioned above) structural change as a significant source of reduction in aggregate energy intensity;

Wing and Eckaus [2004] suggest that in the most recent period innovations embodying information technology in electrical capital goods played an important role in energy intensity decline (see Fig. 8). The issue of reductions in energy intensity is not a simple one.

> There have been a number of energy saving influences: changes in the sectoral composition of the economy, changes in the scale of its constituent sectors, as well as substitution due to shifts in the relative prices of energy and other variable inputs. [...] In particular, a significant portion of the energy-saving technical changes we observe may have been the coincidental result of innovations which were intended to accelerate production, reduce both labor and capital costs, or make use of alternative materials (Wing and Eckaus [2004], p. 19).

The bottom line is that technical progress - possibly together with structural change - has barely succeeded in stabilizing and even marginally decreasing energy consumption *per capita, in high income countries*: see figure 8 and 5 for the U.S. evidence. However demography heavily plays against any stabilization, let alone reduction of total energy consumption and of emissions in the environment.

Demography, energy consumption and emissions

Indeed, the evidence on the past and the most likely projections for the future suggest a massive overall growth of energy consumption (cf. Fig. 6) and of emissions, with some increases even in high income countries: see Fig. 9.

The picture is even bleaker for other sources of emissions: cf. Fig. 7 on the projections concerning total sulfur emissions.

In order to be more precise in identifying the importance of demographic factors in shaping such patterns, one has to identify the elasticity - i.e. the percentage

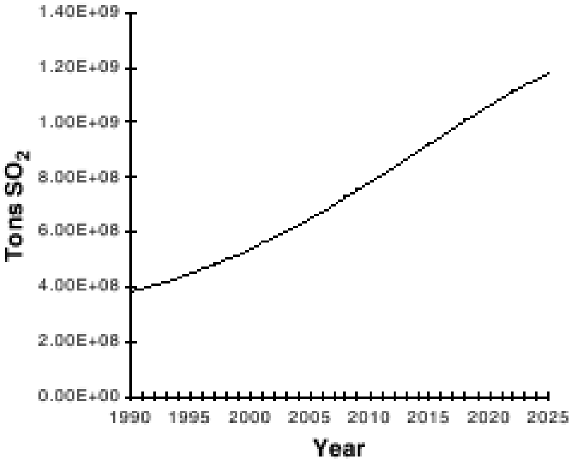

Figure 7: Projected Sulfur Emission Source Stern et al. [1996]

change - in energy use or emissions resulting from a corresponding change in the population. In this respect, when considering per capita emissions, the EKC approach - discussed above - often implicitly assume an elasticity to population of one. Note that, while this is not necessarily the most accurate estimate, it would spell doom for any hope of emission reduction, given the current and projected growth of world population.

Some - including the so-called IPAT model (standing for "Impact Population Affluence per capita Technology": cf. Ehrlich and Holdren [1971]) and others (see Shi [2003], Cole and Neumayer [2004], Dietz and Rosa [1997]) - do indeed account explicitly for demographics effects. The estimates - it turns out - yield elasticities which are in the neighborhood of one. Hence, other things being equal, even neglecting the effects on both energy consumption and emissions of growing per capita incomes, one should expect at least their doubling over the next three decades as a sheer effect of population growth.

3 What can technical progress do? And where does it come from?

Can technological advances reduce energy use and emissions in such a way to compensate the effect of both per capita income growth and demographics?

We have already seen that energy-saving changes in production techniques appeared to have significantly contributed to the fall of energy intensity of GDP

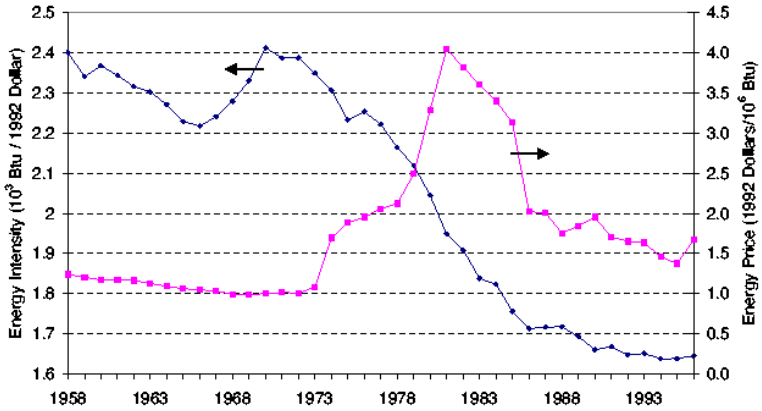

Figure 8: U.S. Energy Intensity and Energy Prices, 1958-1996 Source Wing and Eckaus [2004]

- at least at relatively high levels of development. Could the rate of technological progress be increased to the extent of providing a full compensation for growth and demography?

The answer, we suggest is largely negative.

In order to see that, let us make use of the distinction introduced a while ago in Dosi [1982] between "normal" technological progress occurring within established *technological paradigms* and "extra-ordinary" discontinuities associated with the emergence of new ones. For the purpose of this discussion, diverse paradigms - with their distinct knowledge bases and "trajectories" of advance - tend to be associated with distinct energy sources and modes of generation of heat, electricity and motion. Thus, the generation of electricity through fossil fuel and through nuclear fission are associated with two distinct technological paradigms. Similarly, the use of systems of locomotion based on the internal combustion engine is at the core of the current dominant paradigm of automobile design and production, etc.

In turn, it happens that market prices and other forms of "inducement" are indeed able to "tune up" or slow down the rates of technological change, but this happens within the relatively narrow boundaries set by the nature of the incumbent knowledge bases (the incumbent paradigm). So, for example, the price of energy may have some effects upon energy use in steel production but only within the rather strict limits set by the procedures we currently know on how to transform the iron oxide input. And these constraints to price-induced input savings appear to be the general case in contemporary production paradigms.

A good case to the point is precisely the effect of the "oil shocks" (consider together figure 10, 8 and 6) which did indeed significantly influenced the time series of petroleum consumption. Nevertheless, soon thereafter consumption resumed to

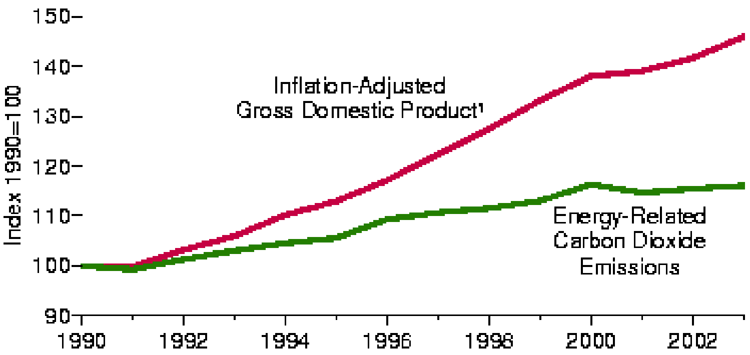

Figure 9: GDP Growth and Carbon Dioxide Emissions Source DOE/EIA [2004]

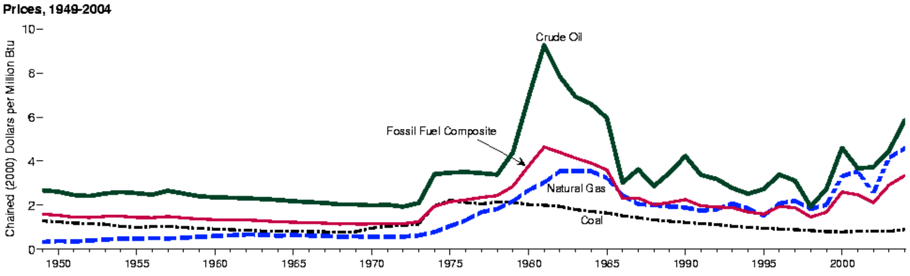

Figure 10: Fossil Fuel Production Prices, 1950-2004 Source DOE/EIA [2004]

its path of almost steady growth.

Still under the "inducement" rubric, public regulations have turned out to be a rather effective mean of influencing the patterns of energy use and of emissions[6]. In a curious paradox in the literature and in a good deal of policy debate one has both underestimated the environmental impact of the negative externalities stemming from production and locomotion and correspondingly overestimated the cost of regulation.

In fact, as Porter and van der Linde [1995] argue, regulatory constraints may not be as costly as one could expect because of the possibility that regulation itself might spur innovative activities and lead to the discovery of "new ways of doing things"[7].

There is a general lesson here: imported price shocks might exert an important

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[6] More generally on the factors influencing the so-called "environmental" innovations see Mazzanti and Zoboli [2006].

[7] The authors support this interpretation providing a series successful case studies.

influence on the energy intensity of particular energy sources but dramatic changes in their use can only be made possible by the emergence and diffusion of new technological paradigms: in the case of electricity generation these are plausibly nuclear power and, eventually, photovoltaic and nuclear fusion; and, in the domain of locomotion, hydrogen-based means of transportation.

Conversely, despite the theoretical inclinations of the economists, the notion that changes in relative prices may induce substitution among inputs - in particular between energy and capital - tend to be a far-fetched idea with little empirical support. The general case is, on the contrary, that of a *complementary relation* between energy resources and manufactured capital (Stern [2004a], Smulders [2005], Landes [1969], Cleveland [2004]; see also the special issue of *Ecological Economics* Vol. 22 Issue 3, 1997. (Daly [1997])). Frank [1959] reports that the correlation coefficient between consumption of energy and manufactured capital is surprisingly high; 0.9995 for the period 1880-1948 in U.S[8]. Indeed, technological advancement has reduced, for a given level of consumption of energy, the need for manufactured capital. Nevertheless, this trend has been counterbalanced by a corresponding trend in mechanization, which has substituted capital to work of manpower or animals.

4 Some Policy Suggestions by way of a Conclusion

The diffusion of different sources and forms of energy as well as the environmental problems to which they are closely related provide an excellent example of the "evolutionary" nature of processes of growth and development. As Kemp and Soete [1990] which points out how the "current environmental problems stem from the accumulation of small effects, which at some point in time appear to exceed the critical boundaries of the ecosystem or at least the public perception of those boundaries. They represent a typical example of an *evolutionary* process in which apparently small events, developing in a certain direction during a long period of time, lead to considerable change."

What is certain in our view is that the cumulative effect of such big and small evolutionary changes will not take care of itself as the most optimistic proponents of "Environmental Kuznets Curve" appear to suggest. Most likely an explosive demography let running until a new "steady state" forecasted somewhere between 12 and 20 billion inhabitants would be sufficient to lead beyond a disaster threshold which in fact some analysts belief that we have already passed (cf. Ehrlich and

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[8] Incidentally, Landes [1969] wonders if it really makes sense to bear all troubles related to capital measurement, when energy use provides such a good proxy.

Ehrlich [1990]).

At the same time, it is hard to see how on the grounds of current technological paradigms one could reach zero net emissions of CO_2 - not to mention *negative* net emissions which would be required in order to reverse the current greenhouse effect.

Hence, unsustainability is looming not for reasons of scarcity as it was claimed three decades ago but in a sense for *lack of scarcity* - at least with respect to energy availability and consumption.

What to do then? Here are some proposals from the modest to the nearly impossible.

First, prices and regulatory measures, we have argued, have limited "inducement effects" but *do* have some. Hence, it is urgent to revive also the regulatory side which nowadays tends to be neglected in favor of more incentive-centered, supposedly "market-friendly" measures such as the development of markets for pollution permits.

As Nelson and Winter [1982] put it:

> "The processes of change are continually tossing up new "externalities" that must be dealt with in some manner or other. In a regime in which technical advance is occurring and organizational structure is evolving in response to changing patterns of demand and supply, new nonmarket interactions that are not contained adequately by prevailing laws and policies are almost certain to appear, and old ones may disappear. Long-lasting chemical insecticides were not a problem eighty years ago. Horse manure polluted the cities but automotive emissions did not. The canonical "externalities" problem of evolutionary theory is the generation by new technologies of benefits and costs that old institutional structures ignore." (Nelson and Winter [1982], p.368.)

Indeed a much greater *bona fide* effort ought to go in the early identification of "negative externalities" and the development of institutions and (generally international) policy measures apt to cope with them.

Second, one should consider high prices of fossil fuels *as a blessing rather than a curse*. Of course there is, associated with it, a serious distributive problem which is not possible to discuss here. However, one should worry even more if some fossil fuels - as especially the most polluting one, coal - remains relatively cheap.

Third, it is unfair and unpractical to demand that emerging economies pay the full cost of "greener" patterns of production: only a mix of (i) mechanisms of preferential treatment of "greener" commodities and (ii) international transfer of less polluting technologies is likely to lower the peaks of whatever EKCs, if they exist at all.

Fourth, we have mentioned above that massive *reductions* in the *levels of net emissions* - to repeat, as such a necessary condition for long-term environmental sustainability - are likely to come only with the development of new technological paradigms.

On the grounds of what we know now the photovoltaic appear to be the most promising one, with, maybe, fusion, in a future further away. The emergence of new paradigms, however, generally demands major advances in basic and applied research sponsored to a good extent by public agencies. Massive "mission-oriented" projects in this area by the ensemble of developed countries are an urgent must.

Finally, possibly the most difficult issue: introduce measures aimed at the fast stabilization of population level well before the "natural asymptotic levels" from current forecasts.

The alternative is probably the "evolution toward collapse" brilliantly described by Diamond [2005] in several occurrences of "suicidal civilization" from the past.

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