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NON-LINEAR RELATIONSHIP BETWEEN ENERGY INTENSITY AND ECONOMIC GROWTH

Jesús Ramos-Martín[1]* and Miquel Ortega-Cerdà**
Institut de Ciència i Tecnologia Ambientals, i
Dept. d'Economia i d'Història Econòmica
Universitat Autònoma de Barcelona
08193 Bellaterra, Spain
and ENT Environment & Management
* jesusramosmartin@yahoo.es
** miquel.ortega@wanadoo.es

Abstract: *From a thermodynamic point of view economies are open systems far from equilibrium, and neo-classical environmental economics is not the best way to describe the behaviour of such systems. Standard economic analysis takes a continuous, deterministic and predictive approach, which encourages the search for predictive policy to 'correct' environmental problems. This is actually what happens with the relationship between economic growth and energy consumption under the dematerialisation hypothesis, so-called environmental Kuznets curve or the inverted-U shaped curve. Rather, it seems to us that, because of the characteristics of economic systems that may follow complex behaviour, an ex-post analysis under the framework of ecological economics is more appropriate, which describes economies as non continuous and non predictive systems and which sees policy as a social steering mechanism. With this background, we present some empirical data on energy intensity evolution for both developing and developed countries. In order to test the hypothesis of a de-linking between economic growth and energy use, we apply here phase-diagrams in which the intensity of use of the year t and that of the year t-1 are represented. This will allow us to check the validity of the continuous relationship, or to check the possibility of the existence of a step-wise behaviour, which can be seen at a lower time-scale, as something similar to the idea of "punctuated equilibrium" for the evolution of systems at larger time-scales.*

Keywords: energy intensity, economic growth, complexity, phase diagram, determinism, punctuated equilibrium, exosomatic energy metabolism.

1. INTRODUCTION

The relationship between energy consumption and economic growth, that is, the energy intensity, is relevant not only for it affects future trends of development of all economies, but especially because it brings to discussion the issue of sustainability.

Although this relationship has been studied in economic thought for long time (see Mirowski, 1989; Cleveland, 1987; and Ramos-Martin 2002 for more details), it is true as Proops

[1] Corresponding author.

(1979) said that the only consideration of energy was as a 'consumption good' or as a 'production factor'. This reveals to be at least not sufficient for understanding the evolution of economies. Therefore the main goal of this paper, after presenting concepts from complex systems theory, is to present data that support the idea that energy intensity evolution should be understood under a complex systems framework.

Many authors have shown that evolution on energy consumption is linked to the creation and destruction of socio-economic structures (see Prigogine, 1962; Von Bertalanffy, 1968; Nicolis and Prigogine, 1977; Proops, 1979, 1983; Prigogine and Stengers, 1984; Schneider and Kay, 1994; Ulanowicz, 1996; and Kay et al., 1999, among others). Thus, a better understanding of the evolution of energy intensity could lead to a revision of our views on the economic internal relations among the different elements of the system, on their relation with the surrounding environment, and therefore to new political approaches to economic and environmental problems.

The structure of the rest of the paper is thus as follows. Section 2 presents two traditional approaches to the relationship between energy and economic growth with their criticisms. The first is supported mainly by ecologists such as Odum (1971) or Costanza (1980) and states there is an strong relationship between economic growth and energy consumption by societies. The second is supported mainly by economists and defends the idea of dematerialisation of the economy as it grows. Section 3 presents some concepts from complex systems theory that are useful to understand the way economies develop, and argues for different explanations to the relationship between energy and growth. Section 4 presents the results for both key developed and developing countries, which are later discussed in Section 5. Finally, Section 6 draws some conclusions and recommends key lines for future research.

2. DETERMINISTIC VIEWPOINTS ON ENERGY AND DEVELOPMENT

Before presenting complex systems theory we may briefly see two approaches to the relationship between energy and economic development which are not fully accounting for complexity. Here some criticism will be developed as well, though a more complete analysis can be found in Ramos-Martin (2001, 2002).

2.1. Energy theories from ecologists

The revival of the interest in biophysical analysis owes much to the work of energy analysts such as Podolinsky and Lotka. In fact, Podolinsky's ideas were advanced for his time. He foreshadowed the idea of modelling labour productivity as a function of the quantity of energy used to subsidise it. He also developed the concept of energy return on energy input under the name of the 'economic coefficient', and he applied it to human beings, concluding that man has the capacity to transform one-fifth of the energy gained from food into muscular work. This result can be seen as a biophysical foundation of the theory of value. As Martinez-Alier (1987: 51) says, "in economics Podolinsky thought that he had reconciled the Physiocrats with the labour theory of value". His concepts, as Cleveland (1987) notes, have proved to be powerful and have been used later by some other biophysical analysts, such as Cleveland et al. (1984) and Odum (1971). For example, his distinction between exosomatic[2] and endosomatic[3] energy flows,

[2] Use of energy sources for energy conversions outside the human body, for societal metabolism,

later proposed as a working concept for the energetic analyses of bio-economics and sustainability by Georgescu-Roegen (1975), is helpful in the analysis of exosomatic energy metabolism of societies. Lotka's contributions to the debate was basically his statement that natural selection tends to:

(i) Increase energy flow through biological systems
(ii) Increase energy efficiency of biological processes.

More specifically, the original words of Lotka (1922: 148) were that "natural selection will operate so as to increase the total mass of the organic system, and to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system so long as there is present an unutilized residue of matter and available energy". There are two approaches to Lotka's analysis. One is developed by Odum, arguing in favour of a universal law of evolution. The other sees Lotka's contribution without determinism (O'Connor, 1991; Buenstorf, 2000), but as a mere description of past regularities that can help to explain evolution, in a more phenomenological way.

Odum referred to Lotka's principle as the 'maximum power principle' (Odum and Pinkerton, 1955), and took it as an universal law that states that "any organism, or system, that invests energy very rapidly but inefficiently, or very efficiently but not at a high rate, will be less competitive in natural selection than that which works at some intermediate, but optimal, efficiency, so that the useful power output is maximum at an intermediate process rate" (Hall et al., 1986: 63). This principle, plus the energetic theory of value introduced by Odum (1971, 1996) and developed later by Costanza (1980) which introduced eMergy (embodied energy) as a measure of value and in which those authors argued that 'available energy' would be the ultimate limiting factor[4], led some energy analysts to hypothesise that economic systems try to maximise power and therefore energy consumption for their development. This would lead to a very strong relationship between economic growth and energy consumption, as economies try to develop further.

Hall et al. (1986) use a battery of empirical results for the USA and other countries in which they find that the correlation between GNP and fuel use is about 99%. However, the authors are aware of the possibility of being misunderstood and, therefore, they modify their conclusion by saying that the correlation found "might reflect *time trends* in fuel use and the GNP in a growing economy rather than a close relation between fuel use and the GNP produced in a given year or set of years" (Hall et al., 1986: 51, emphasis in the original). In any case, even accepting there is this relationship between GNP and energy consumption, this is not a linear relationship. As Giampietro and Pimentel (1991) noted, changes in the levels of energy dissipated by societies seem to imply jumps in the energy expenditure and the size of the system. "For example, there is a jump in the level of energy expenditure from 15,000 kcal/day per capita

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but which are still operated under human control.

[3] Use of energy needed to maintain the internal metabolism of a human being, that is, energy conversions linked to human physiological processes fuelled by food energy (Giampietro et al., 2001).

[4] Being the ultimate limiting factor, (free) energy would be the source of value, as well. The relative price of a good could be explained by the relative embodied energy cost. This theory neglects, however, that "no single factor, be it labor, utility, or energy, is both a necessary and sufficient condition for economic value" (Hall et al., 1986: 69).

in a prosperous rural village to 70,000 kcal/day per capita for urban population. There appear to be no stable intermediate values" (Giampietro and Pimentel, 1991: 141). This argument is exactly the one defended by those who argue for the application of punctuated equilibrium to the development of the energy metabolism of societies as we will see in Section 4.

If we believe Odum's interpretation of Lotka's words, we might expect that as economies evolve they will use larger and increasing amounts of energy (unless the efficiency effect outweighs). This would have an increasing impact upon the environment due to the increased amount of dissipated energy and therefore of entropy generation. This has recently led Odum to ask, following Daly and others, for a reduction in energy consumption, not just in per capita terms, but also in absolute terms. That is, Odum's *Prosperous way down* (Odum, 2001).

2.2. The debate on the dematerialisation of the economy

Recently, the issue of the dematerialisation of developed economies (the reduction of material as well as energy intensities over time) has gained popularity in the field of ecological economics. For example, the hypothesis that the use of less energy and resources to produce the same economic output could represent a solution to the ecological compatibility of future economic growth was discussed in a special issue of the journal *Ecological Economics* dedicated to the so called Environmental Kuznets Curve (Vol. 25, 1998). This idea is strongly supported by technological optimists from the perspective of the industrial ecology (e.g. Von Weizsäcker et al., 1997, Hinterberger and Schmidt-Bleek, 1999).

The so-called hypothesis of "intensity of use" was first put forward by Malenbaum (1978) and states that income is the main factor that explains the consumption of materials. That is, during the process of economic development, countries would tend to increase consumption of energy and materials at the same rate as growth in income, until one defined level of income is reached. Beyond that level, however, we have to expect a de-linking between economic growth and the consumption of materials. That is, further increases in the level of output will no longer be followed by increases (at the same rate) of energy and material consumption. This is the so-called inverted-U shaped curve or an Environmental Kuznets Curve (EKC)[5]. According to this hypothesis, developed countries should be 'dematerialising', meaning that they would be decreasing their use of materials per unit of output, because they have already reached the threshold value of income (or the 'peak' year in historic series). In contrast, developing countries would still be 'materialising', that is, increasing their materials and energy intensity.

The discussion on dematerialisation is specially relevant since the EKC is believed to be able to link a measure of environmental impact (e.g. the requirement of inputs for the economy such as energy and the resulting pollution, i.e. CO_2) to a measure of wealth generation (e.g. the GDP). So, if the energy intensity of modern economies is actually reducing over time, the same will occur for the 'carbon intensity', and other variables reflecting pollutants.

Most of the studies on the intensity of use assume a quadratic relationship between the evolution of the (GDP) and the biophysical throughput. The majority of these studies show:

(1) a growing throughput associated with growth in GDP in the early stages of development, and
(2) a decreasing growth in the throughput compared with the growth of GDP, for the main

[5] Stern et al. (1996) offers an introductory literature review of the EKC. See also de Bruyn et al. (1998), Opschoor (1997), Arrow et al. (1995), and Ayres (1997).

developed countries (the so called phase of dematerialisation).

That latter phase would imply that economies become more and more efficient in their use of exosomatic energy, in their exosomatic metabolism, leaving room, therefore, for more growth and development in the future without the side effects occasioned by energy dissipation. This is a very optimistic view of the evolution of economies in energy terms.

Traditionally (Mielnik and Goldemberg, 1999; Opschoor, 1997), the de-linking has been explained by three factors:

1) Structural change in the economy, shifting from high energy intensity sectors to lower intensity ones;
2) improvement in energy efficiency;
3) changes in consumption patterns

This 'income determinism' (Unruh and Moomaw, 1998) implies, according to its defenders, that an increase in economic growth is a good policy for the environment[6]. In fact, it will bring, sooner or later, a de-linking from the consumption of energy and materials and wealth, which will lower the environmental impact of economic activity. This result, found for some developed countries, is therefore applied in a deterministic way to other economies, by extrapolating it in time and in space. Thus the analysis gives the same kind of 'universal' advice to policy makers: growth has to be seen as something positive for the environment.

Despite the optimism derived from the EKC hypothesis, there are several problems with it. In particular 2 points are related to the present analysis:

(1) The expected de-linking implies only a week dematerialisation (per unit of GDP) but not a strong or absolute dematerialisation (decrease in the metabolism of the system).

(2) The de-linking occurs only after the country has reached a certain threshold of income and consumption of energy and materials per capita. Looking at world values, such a threshold is a very high one for the majority of the world's population[7]. From an environmental point of view the second point is rather relevant. This is because the final size of the throughput of the world economy will be determined by *when* all countries will reach the expected threshold level (admitting that this will be possible).

To make things more difficult, three additional explanations should be added to the three presented above for explaining the dematerialisation of developed countries shown by the historical series. The first explanation is linked to the idea of 'trans-materialization'. This is that the economies of many developed countries are using new resources (or old resources in a different way). This can imply that the changes we track using old indicators of pollution do not necessarily reflect the actual environmental stress induced by modern economies. In this case,

[6] Stern et al. (1996) said that one of the major problems of the EKC is this assumption of unidirectional causality from growth to environmental quality, which is assuming there is no feedback from the state of the environment to economic growth.

[7] Here, for instance, as Agras and Chapman (1999) mentioned, too much attention has been paid to shift the turning point to the left (meaning start de-linking with lower levels of GDP), but reducing the overall level of pollution, which is more important, has been given too little attention.

therefore, EKCs simply *do not see* what is going on in reality. The second explanation is similar, pointing again at a poor representation of the phenomenon when using EKC. More and more in the last decades a certain fraction of the economic activity required for sustaining societal metabolism of developed countries, especially the most energy and resources intensive, have been shifted to developing countries (for a fuller explanation of this, including statistical data supporting their views, see specially Stern et al., 1996; Suri and Chapman, 1998; and Muradian and Martinez-Alier, 2001). In this case, we simply deal with an externalisation of the phase of possible re-materialisation of the economic process (the environmental impact linked to the production of capital goods is moved to developing countries). Put another way, we are not dealing with a real process of dematerialisation, but just an artefact generated by a sort of *epistemological cheating*. That is, it would be an example of the internationalisation of environmental externalities, or put in other words, an example of 'cost-shifting successes' from northern countries to poorer ones, allowed by social asymmetries in the distribution of (mostly de facto) property rights, income and power (Martinez-Alier and O'Connor, 1999). Damage to the environment due to 'externalised economic activities' simply does not show up in the analysis made at the national level. In fact, as empirical data shows (Muradian and Martinez-Alier, 2001: 289), "the North's economic growth goes together with: (a) increasing consumption of non-renewable resources coming from developing countries; and (b) worsening terms of trade for exporting countries specialized in non-renewable resources". As Stern et al. (1996) noted, this strategy of specialising in low energy and resource intensity activities by rich countries is not applicable to the world as a whole; therefore not every country can experience a de-linking phase. In fact, when trade is incorporated into EKC studies (Suri and Chapman, 1998) the turning point of the curve for energy consumption is estimated to be about $224,000 per capita, which is a level unlikely to be attained by any country in the near future. Despite that evidence, even "when economic growth has made people wealthy enough (to clean up the damage done by growth) it may be 'too late to be green'" (Muradian and Martinez-Alier, 2001: 284).

The third explanation is related to the changes over time in the fuels used. Cleveland et al. (1984), Hall et al. (1986), Kaufmann (1992), and Cleveland et al. (1998) have studied in detail this aspect of the historical de-linking of some industrialised economies, leading to the conclusion that an important part of the reduction is due to the change in the fuel used, from low to high quality (i.e. from coal to oil). The different qualities of the fuels (the capacity of doing useful work per heat equivalent unit) can influence energy efficiency (Hall et al., 1986). For instance, in the case of the USA, 69% of the change in the energy intensity since 1929 is due to the changes in the type of fuel used (Cleveland et al., 1984). More specifically, we can say that much of the decline in the energy intensity has been due to the ability to expand the use of higher quality fuels, and this has upper limits (the availability of scarce high quality energy resources). Nevertheless, this factor is usually forgotten when analysing the EKC hypothesis.

In fact, even admitting that some countries are in a dematerialisation phase (as shown by Jänicke et al., 1989), the entire debate may remain sterile according to the insight provided by De Bruyn and Opschoor (1997). Indeed, some developed countries are in a re-materialisation phase, after experiencing a phase of dematerialisation during the previous years. This, 're-linking hypothesis' implies that an inversion in existing trends could always occur also for those countries that at the moment are still in a de-linking stage. According to this hypothesis, the curve of the throughput versus the per capita GNP, would therefore not follow the inverted-U shaped curve, but rather an N-shaped one (depending on the time window used for observation). That is, the N-shaped curve implies 3 phases:

(1) The use of resources grows in parallel with income growth.
(2) The phase of capitalisation is followed by a reduction in the rate of materialisation, in which the major increase in output is in the service sector.
(3) At this point a new materialisation phase can start at any moment (when introducing new activities in the economic process). This phase will continue until new technological innovations (increases in the efficiency for the new activities) will allow for a new de-linking.

Whether or not developed countries are facing a temporary de-linking phase that may be followed by a re-linking one is the issue here. If we believe in EKC we should not worry from an environmental point of view since the tendency would be to de-link as economies grow. However, if we are not happy with this approach, let us explore an alternative explanation of the relationship between economic development and the exosomatic energy metabolism of societies.

3. COMPLEX SYSTEMS VIEW

3.1. Economies as complex systems

Complex systems theory provides some useful tools and concepts for our analysis[8]. Following Kay and Regier (2000), we can say that complex systems are characterised, as we shall develop later, by some (or all) the aspects that follow:

- non-linear behaviour (because of feedback);
- hierarchical structure (the system is nested within a system and is made up of systems);
- internal causality (self-organising causality characterised by goals, positive and negative feedback, autocatalysis, emergent properties, and surprise);
- the fact that there may not exist equilibrium points;
- multiple attractor points (steady states) are possible;
- they show catastrophic behaviour, with bifurcations and flips between attractors; and even chaotic behaviour, where our ability to forecast and predict is limited.

Economies are complex adaptive systems, that is, composed of large and increasing number of both components and of the relationships between them. Economies are also teleological systems (they have an aim, or end, the telos), they tend to maintenance, development and they are capable of incorporating the guessed consequences of their fulfilment into the present decisions and definitions of new tele, they are thus anticipatory. They also learn from mistakes and from present developments, and they react, by changing both the actions undertaken and the tele defined; they are thus self-reflexive. They also have the ability to adapt to new changing boundary conditions, but they may *consciously* alter the boundary conditions (i.e. in their relation with the environment). This is why the economy, as a human system, can be understood as a complex, adaptive, *self-reflexive*, and *self-aware* system (see Kay and Regier, 2000, for more details).

The study of the evolution under the complex system framework will help us to understand better the relationship between the development of economies and their energy

[8] For a deeper analysis on economies as complex systems, see Ramos-Martin (2002).

metabolism (i.e. energy dissipation), what Georgescu-Roegen (1971) called *exosomatic evolution*, and has been later called 'societal metabolism' (Fischer-Kowalski, 1997).

3.2. How energy intensity evolution could be understood in a complex system framework?

Economies are open systems. This means they receive inflows of both energy and materials. Economies use that incoming energy to develop and build new structures, they self-organise by dissipating low entropy energy. This facts leads economies to be far-from-equilibrium in thermodynamic terms (Nicolis and Prigogine, 1977; Prigogine and Stengers, 1984). For the system to maintain its organisation, it is necessary to dump the entropy generated into the environment, making compatible entropy generation and order. Therefore, in the process of the self-organisation of open systems, two contradictory effects exist. First, there is the inherent tendency towards increasing energy dissipation, whereas, on the other hand, these systems also show a tendency towards an increased efficiency in the rate at which energy is dissipated.

Economies, as we have stated in the later section, could behave as complex systems as well. If this statement is true, typical complex systems patterns should be observed in key variables that describe their state.

Complex system theory establishes that sometimes smooth and continuous behaviour is possible, but this is not always like that. For example a small change on GDP, could lead to a great disparity of results on energy intensity: coming from big changes to almost no changes at all.

The hierarchical structure of the economy, as well as the working of the feedback loops between the different hierarchical levels, induces non-linear[9] behaviour in the system. This is so because positive feedback loops might generate self-reinforcing mechanisms. This non-linear behaviour is not only induced by external shocks as is normally implied by economic theory, but also by internal causes within the system. Both non-linear behaviour, and far from equilibrium situations lead to the existence of a multiplicity of stables states (Proops, 1985) or attractors. An attractor represents a region in which the behaviour exhibited by the system is coherent and organised (Kay et al., 1999). Once the system reaches the attractor, it fluctuates around it and its parameters move only short distances, at least for a certain period of time. This is known as 'lock-in', and prevents the system from taking another trajectory for a period of time (Dyke, 1994; Kay et al., 1999). The fact that a particular system is stabilised around one attractor point constrains the future available trajectories and attractors, by paving the path for future developments, in an example that history counts. If we study the evolution of energy intensity and we state that the system is on an "attractor point" some changes in, for example, GDP, will not always lead to changes in the studied variable. Energy intensity will remain almost constant, in opposition to the continuous change expected from the EKC theory.

[9] Understood here as non-continuous; that is, there are changes that do not occur smoothly. The term non-linear is used since it is the one found in the literature, although non-continuous might be considered as more proper.

This situation leads to a series of 'bifurcation'[10] points (Prigogine, 1987), in which, for given boundary conditions there are many stable solutions. Following Faber and Proops (1998: 88, 89) a "bifurcation may occur when the stable equilibrium for a dynamic system is sensitive to changes in the parameters of the system". Thus, when the parameter goes beyond a critical threshold, the system becomes most sensitive and therefore unstable. In this case, tiny perturbations may trigger drastic changes (Dalmazzone, 1999), leading to a set of new different stable equilibria to which the system might eventually flip.

Over half a century ago, Schumpeter (1949) understood non-linear evolutionary development and discontinuity by means of his theory of creative destruction. This idea has been later named 'punctuated equilibrium' by some analysts (Gowdy, 1994), using the same term that is in use in palaeontology to describe this step-wise evolution (Eldredge and Gould, 1972; Gould and Eldredge 1993).

We hypothesise here that this kind of behaviour may be found when analysing the evolution of energy intensity, reflecting deeper changes in the system that are not fully covered by that variable and that should be analysed by including other variables accounting for the relation between economic structure, informational / organisational issues (including knowledge generation), and resources requirement. Something that is not done here.

One way of analysing the existence of this discontinuity is by means of a phase diagram. This methodology has been used in the case of CO_2 emissions (Unruh and Moomaw, 1998), and in the case of energy intensity (De Bruyn, 1999; Ramos-Martin 1999, 2001). The phase diagrams are intended to show whether the development of certain variables over time are regular or irregular. They are also useful to find if there are or not attractor points. If so, we can check how persistent are those attractors as well as the magnitude of the fluctuations around them (Unruh and Moomaw, 1998). A useful approach, as the authors said, is a time-evolving space in which we compare the evolution of the variable (i.e. energy intensity) in the previous year (y-axis) with that of the current year (x-axis). This representation allows us to see whether we are facing a 'punctuated equilibrium'-like behaviour or not. If we are, then we will see how the variable concentrates around certain attractors. If not, the evolution of the variable will be different, showing a more or less straight line. As the results from de Bruyn (1999) indicate, several developed economies seem to show attractor points for energy intensity. This means that the process of development is step-wise, and therefore, we should focus future empirical research on identifying the attractor points and the causes of the flips between them.

For instance, one could think that the natural tendency of economies is to dissipate more energy as they develop and build new structures (i.e. they organise). However, that tendency could be partially outweighed by efficiency gains (i.e. from technical development) that would make possible energy intensity to concentrate around certain attractors for a while, until the efficiency gains were completely realised. Later, energy intensity would increase again as the economic system develops further and makes use of new low entropy energy sources. That is, if punctuated equilibrium-like behaviour holds for energy intensity, meaning that the relationship between energy and economic growth is step-wise and largely unpredictable, we should be able

[10] May and Oster (1976) first introduced the concept of bifurcation when analysing the behaviour of chaotic systems.

to see attractors points when plotting that variable. This is what we do in the next section.

We believe the idea of "punctuated equilibrium" suits better to that evolutionary time scale. However, our hypothesis is that we may also find this step-wise behaviour of energy intensity at lower hierarchical levels of the economic system and at lower time scales. This is why the results presented here just pretend to test that behaviour at the national level but with a much smaller time span than the evolutionary one. The idea behind is that we may find historical regularities at different levels of the system (something called "invariance of scale"), and we leave for future research the analysis of even smaller compartments of the system and smaller time frames.

4. PRESENTATION OF RESULTS

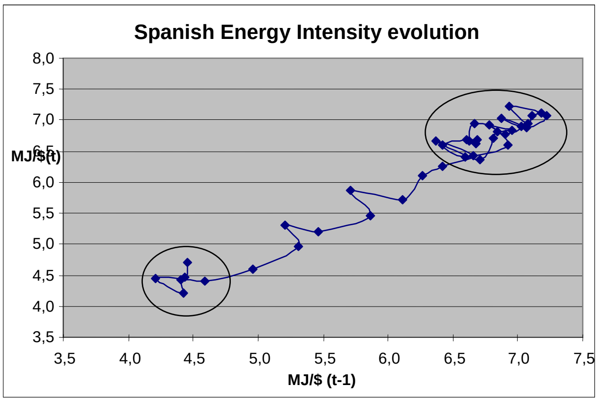
So far we have seen the theory about the relationship between energy and economic development. Let us see some data on the evolution of energy intensity that may allow us to check whether this relationship is lineal as defended by Odum, it follows an hypothetical EKC and therefore there is no worry about the environment, or rather is step-wise as shown by De Bruyn (1999) for Germany and Ramos-Martin (1999, 2001) for Spain.

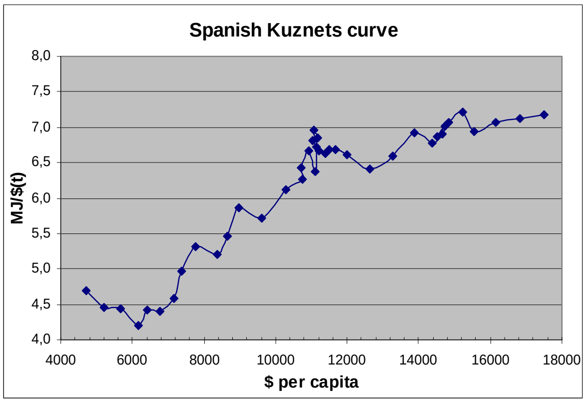
The data[11] gathered refers to the time period between 1971 and 1999 for non-OECD countries, and the period between 1960 and 1999 for OECD countries. The variable accounted for is 'energy intensity', measured as Total Primary Energy Supply (TPES) per thousand 1995 dollars GDP measured in Purchasing Power Parity (PPP); that is TPES/GDP (tonnes of oil equivalent per thousand 1995 US$ PPP). In order to present the data of energy in international units we must convert tonnes of oil equivalent (toe) into mega joules (Mj). For that we apply the following conversion factor: 1 toe equals 41,800 Mj. Therefore, we express energy intensity in Mj/GDP (mega joules per thousand 1995 US$ PPP) – [1 Mj = 10^6 joules].

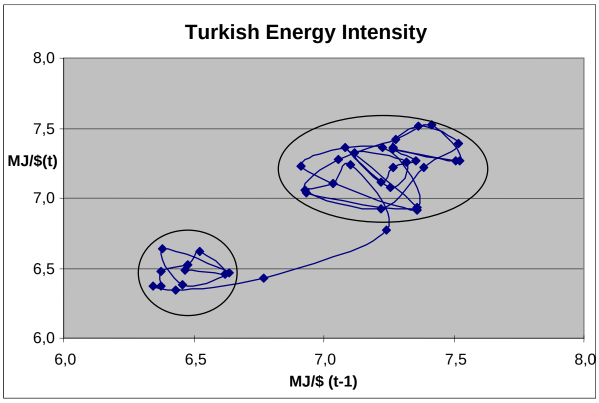
Here we will just see the case of three developed and three developing economies. From OECD we have a low income country (Turkey), a medium income one (Spain) and a high income representative (UK). In the case of non-OECD countries, we have chosen one country for Latin America (Brazil, medium income), one for Africa (South Africa, high income), and one for Asia (India, low income). This will give us a synthetic overview of energy intensity in different kind of countries.

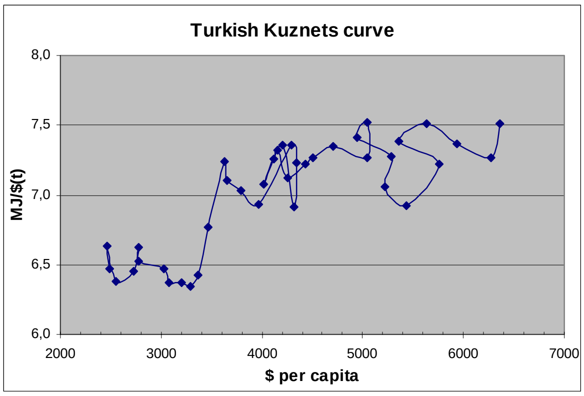
[11] Taken from International Energy Agency (IEA), specifically from OECD (2001), *OECD Statistical Compendium on CD-ROM*, edition 2. Paris.

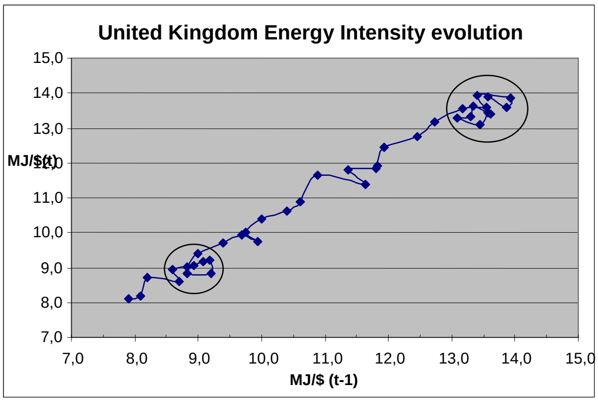
4.1 OCDE countries

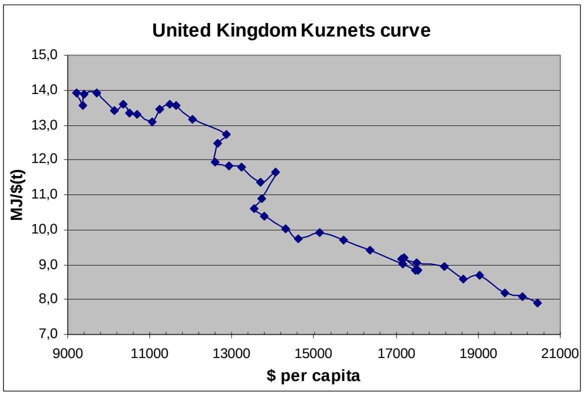




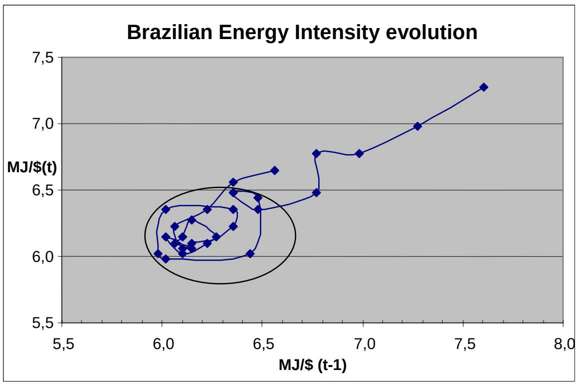


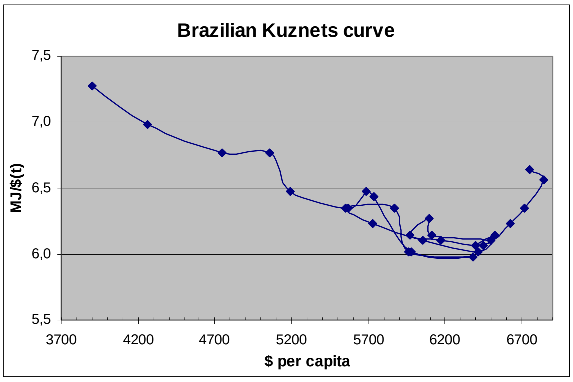


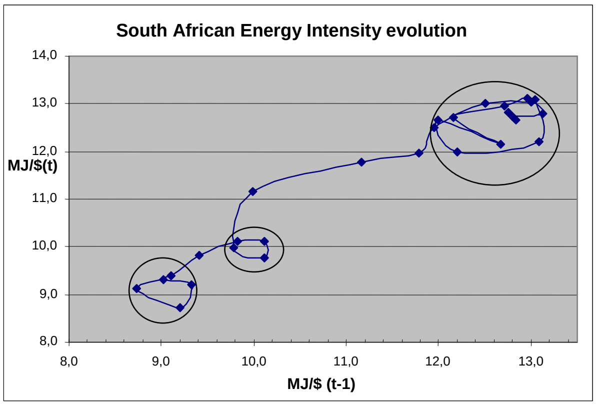


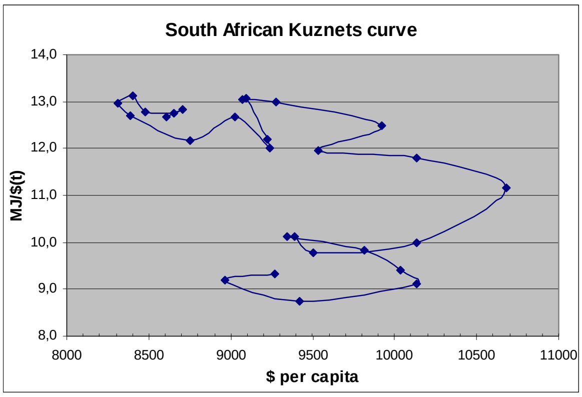


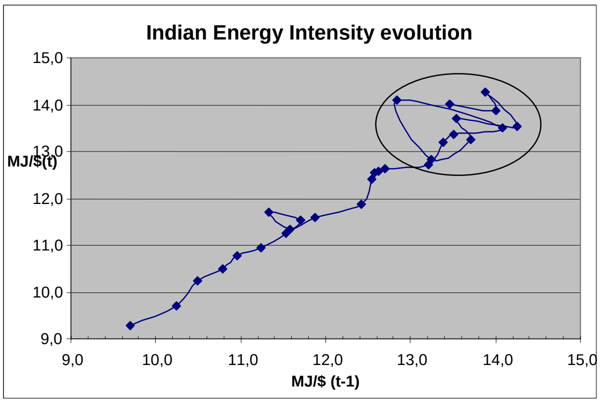
4.2 non-OECD countries

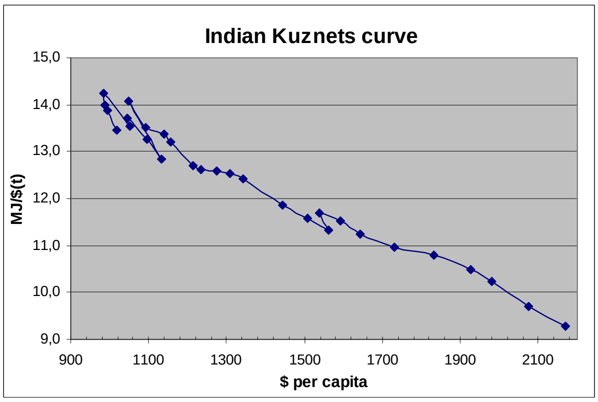












5. DISCUSSION

From the data presented in the last section we can get one preliminary result that is finding a “step-wise” behaviour for energy intensity at the hierarchical level of the nation state and for a particular time window. That is, even in the cases where energy intensity is decreasing over time, it is possible to see that the variable does not show a continuous behaviour. This fact contradicts the idea of the existence of a hypothetical environmental Kuznets curve for energy intensity. In this regard we want to highlight the fact that this non-continuous behaviour unfolds in certain patterns that may be identified. This would help in grouping countries according to that particular pattern in a way that would be more useful for policy making regarding the use of energy.

Even though it is not the intention of the paper to analyse the case studies presented, but just to use them to support our theoretical hypothesis, some words can be said. Should EKC hypothesis apply, we should not expect low income countries like India and South Africa to lower their energy intensity. On the other hand, we should expect that Spain would decrease its energy intensity, but this is not the case. The other three cases more or less follow a pattern compatible with EKC; that is, the UK is decreasing its intensity, and both Turkey and Brazil are increasing it (although the later one just in the recent years). It seems to us that the underlying processes that are driving the evolution of energy intensity cannot be explained just by the process of economic growth. Rather, we think that internal causes in each country explain that behaviour. In this sense, for the UK one might expect that structural change, change in the type of fuels, and ‘cost-shifting success’ are the main explanations for lowering the energy intensity. This process would be followed by an increase in less developed countries (where we include Spain) leaving the case of India for further analysis. In summary, as shown in Section 3.1. economies show non-linear behaviour, internal causality also drives their changes, they have multiple attractors available and therefore some kind of catastrophic behaviour is expected (i.e. South Africa). All these factors make necessary, as is mentioned in next section, deeper case study analyses for the different economies, focusing in identifying the attractors and explaining the flips between them.

Apart from that, the presence of step-wise behaviour at this level supports our hypothesis, presented before, that this kind of behaviour would be found at different hierarchical levels of the system considered. It would be found at evolutionary levels (being then appropriate to use the term ‘punctuated equilibrium’), but it would also be found at smaller levels. We suggest that even at smaller levels than the one analysed here they might be found, and this would be part of our future research. Should we find this result, we shall be able to say that ‘invariance of scale’ applies for the variable energy intensity.

We would also like to stress the fact that attractor points are not found for all countries analysed, either developed or developing. However, we decided to show in this paper only examples of attractors. This is not a limitation of the present approach since the underlying behaviour (non-continuity) is reflected anyway[12].

With these results we think the use of only EKC is not sufficient for explaining the underlying causes that drive the evolution of that variable. This is why we defend here the use of phase’s diagrams to help understanding the development of such variables in different ways.

[12] Data on a wider group of developed and developing countries is available from the authors upon request.

6. CONCLUSION

The fact that economies show non-linear behaviour in key variables and step-wise development at different hierarchical levels makes the use of the ‘punctuated equilibrium’ hypothesis useful at a higher scale, since it allows one to represent the multiple meta-stable attractors that are available for economic systems when admitting the openness of future.

This “step-wise behaviour” on energy intensity suggest that the only consideration of energy as a ‘consumption good’ or as a ‘production factor’ is at least not sufficient for understanding the evolution of economies.

Energy intensity is a key variable that could be used as an indicator of the change on socio-economic structures, monetary structures or environment-economy relations. It could be used as an indicator of the appearance of new structures too. Available data and their analysis supports the idea that energy consumption can be seen as both a requirement and a cause of the further complexity of economic systems.

We however do not think energy dissipation is “the” cause of complexity, but just another cause of economies evolution over time. It can be seen as a variable that is reflecting the surface of the system’s unfolding, but that is incapable of explaining why and by which means is doing it. More research is needed to investigate therefore how economies evolve, and what triggers the flips between the different attractors. This will require analysing deeply the relation between economic structure, informational / organisational issues (including knowledge generation), and resources requirement.

Moreover, even though we only speak of showing the surface of the evolution of economies, more analysis is also required with this respect. This is why we see the present results just as part of a full evolutionary analysis of energy intensity for economies, which will comprise several hierarchical levels and time frames. In particular a case study analysis is needed for a single economy in order to check our hypothesis of historical regularities and “invariance of scale”; that is, to find step-wise behaviour in the different levels analysed. This will be part of the authors future research.

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