This is an Accepted Manuscript version of the article published in the journal Ecological Economics. The final published version is: Ramos-Martin, J. (2001a): "Historical analysis of energy intensity of Spain: from a "conventional view" to an "integrated assessment", *Population and Environment* , 22(3): 281-313.
http://dx.doi.org/10.1023/A:1026672513730

Historical analysis of energy intensity of Spain: from a "conventional view" to an "integrated assessment"

Jesús Ramos-Martín

Keele University, Staffordshire, ST5 5DX, UK.
E-mail: jesusramosmartin@yahoo.es

Abstract

Understanding the relationship between the Gross Domestic Product (GDP) and the throughput of matter and energy over time in modern societies is crucial for understanding the sustainability predicament as it is linked to economic growth. Available data on changes in energy use and economic performance in Spain (over the period 1960–1996) shows that Spain has been increasing its energy intensity during this period contrary to the hypothesis of an "inverted-U shaped curve of intensity of use." Will this increase be followed soon by a decrease? Or rather should we look for alternative explanatory hypotheses and study changes in the dynamic energy budget of Spain as movements between 'attractor points'? If this is the case, what are the main mechanisms generating such a behaviour? Three nonequivalent methods of analysis complementing each other are used to deal with these questions.

Keywords: Spain; dematerialization; EKC; punctuated equilibrium; energy intensity; attractor points; societal metabolism.

Introduction

Recently, the issue of dematerialization of developed economies (the reduction of material 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 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 industrial ecology (e.g., Von Weizsäker et al., 1997).

The "intensity of use" hypothesis was first put forward by Malenbaum (1978). It states that income is the main factor that explains 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 a defined level of income is reached. Beyond that level, however, it is expected that economic growth and the consumption of materials will not be linked. 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. According to this hypothesis developed countries should be "dematerializing"—meaning that they are 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). On the other hand, developing countries are still "materializing."

However, as discussed more fully below, there are several problems with the studies used to support this hypothesis: (1) The results are based on the ceteris paribus assumption applied to historical cases and therefore are difficult to generalize into the future. That is, they do not take into account the Jevons Paradox (Jevons, 1990) which assigns lesser importance of improvements in (energy) efficiency for reducing total energy consumption. (2) A reduction of consumption per unit of output does not imply a reduction in total energy consumption. In fact, the impact on the environment will be determined by the relative speed at which the rate of consumption per unit of output is reduced compared to the speed at which the rate of production of output per capita grows. (3) The variables considered in the historical cases considered reflected only some of the relevant parameters determining the relationship between Gross Domestic Product (GDP) and the throughput of matter and energy of countries. In particularly, they do not consider changes in the household sector. This is why, in this paper, I present: (1) the conventional analysis of this relationship, using the definition of the concept of energy intensity used in these "conventional" studies; (2) a representation of changes based on an evolutionary approach; and (3) an integrated assessment, in order to generate non-equivalent descriptions of the same process.

The discussion on dematerialization is especially relevant since the Environmental Kuznets Curve is believed to be able to link a measure of environmental impact (e.g., CO2 pollution) to a measure of wealth generation (e.g., the GDP). As a result, if the energy intensity of modern economies is actually reducing over time, the same will occur for the 'carbon intensity.'

The case of Spain is relevant since the development of its energy intensity over time, at the moment, is not following the hypothesis of the Environmental Kuznets Curve (EKC). Trying to understand the reasons for this anomaly provides an opportunity to analyze the robustness of the hypothesis of dematerialization of modern economies.

In the following analysis I consider the economic process as the production and consumption of goods and services through the transformation of energy and matter. Daly (1991, p. 36) has called this transformation the "throughput". Throughput is the entropic physical flow of matter-energy from nature's sources through the human economy and back to nature's sinks. Throughput can also be described as the "metabolic flow" of society following the ideas of Georgescu-Roegen.

The following analysis of changes in intensity of use in Spain is simplified by considering the level of throughput of a country as an indicator of its environmental impact. Lack of detailed data on different types of pollution and their location specificity prevents the possibility of performing parallel studies that would track changes in different material throughputs linked to these pollutants. This is the reason why, in general, data on consumption of energy and resources use are used as a proxy for the consequent output. That is, assessments of the input side of throughput are used as indicators of environmental impact. This is a quite reasonable choice, especially when dealing with CO2.

Most of the studies on intensity of use assume a linear relationship between the evolution of the GDP and biophysical throughput. As noted above, the majority of these studies show: (1) a growing throughput associated with the 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 developed countries (so called phase of dematerialization).

However, evidence from the German case shows that sometimes the relationship between material throughput and GDP is not continuous, but shows some 'jumps' (see De Bruyn, 1999). Here I test for continuity of this relationship for the Spanish economy in Section 3, after presenting data showing the increase of its energy intensity in Section 2. Non-linearity in the energy metabolism of Spain can be explained by analyzing the energy intensification process. In order to do that, I apply here the phase diagram methodology used by De Bruyn (1999). This method represents the intensity of energy use of the year t and that of the year t − 1. This alternative methodology makes it possible to check the continuity of dematerialization, as well as the alternative hypothesis of alternate phases of dematerialization and re-materialization around certain 'attractor points.' This latter theory is termed the theory of punctuated equilibrium (Eldridge & Gould, 1972; Gowdy, 1994).

Finally, I use an integrated assessment of exosomatic metabolic rates of various economic compartments to characterize the economic development and energy metabolism of Spain. This model has been presented in Giampietro and Mayumi (first two papers of this issue), and it also used by Falconí (this issue) to assess the recent history of economic development in Ecuador. The relevance of this additional non-equivalent analysis is that it provides new insights for the same facts (i.e., the changes in economic development and energy intensity of Spain presented in Sections 2 and 3). New insights are provided by including the household sector which is often neglected in EKC analysis and by combining biophysical indicators (such as human time allocation related to energy consumption per unit of human activity) with economic indicators.

Therefore, the structure of the rest of the paper is as follows:

• Section 2 provides a brief review of the literature on the theoretical explanations of dematerialization. It also discusses the evolution of energy intensity of Spain compared with other countries, using the conventional approach.

• Section 3 deals with the 'evolutionary' perspective of dynamic systems, showing the phase diagram for Spain and the non-linearity that characterizes the development of energy intensity in Spain.

• Section 4 presents an integrated assessment of exosomatic metabolic rates of different economic compartments, pointing to the special relevance of the demand-side (household sector). This section compares Spanish economic development to that of Ecuador presented earlier by Falconı´ (this issue). When considering the dynamic of capitalization of the various sectors linked to demographic changes, it becomes clear that Spain followed the other side of the possible bifurcation in economic development: It was characterized by a positive spiral in which surplus generated more surplus at a faster rate than population growth.

• Finally, I include an Appendix that identifies the data sources and discusses the methods of data analysis.

The conventional representation of energy intensity

The Theory

The relationship between GDP and the throughput of matter and energy has been analyzed mainly by using the ratio of energy intensity defined as the total primary energy supply divided by GDP. This relation shows the inverted-U curve for some economies, leading, then, to the generalized concept of de-linking, or dematerialization.

Traditionally the de-linking has been explained by three factors: (i) structural change in the economy as it shifts from high energy intensity sectors to lower intensity ones; (ii) improvement in energy efficiency; (iii) changes in consumption patterns (Mielnik & Goldemberg, 1999, p. 307; Opschoor, 1997).

According to its defenders, this 'income determinism' (Unruh & Moomaw, 1998, p. 222) implies that an increase in economic growth is a good policy for the environment. In fact, proponents of the EKC hypothesis propose that sooner or later economic growth will result in a de-linking of the consumption of energy with materials and wealth, and this will lower the environmental impact of economic activity. However, there are several problems with the EKC hypothesis. In particular 2 points are related to present analysis:

(1) As noted by Giampietro and Mayumi (second paper of this issue) and Pastore et al. (this issue), the expected de-linking implies only a weak dematerialization (per unit of GDP) but not a strong or absolute dematerialization (decrease in the metabolism of the system).

(2) The de-linking occurs only after the country reached a certain threshold of income and consumption of energy and materials per capita. Looking at world values, such a threshold is very far off for the majority of world's population.

From an environmental point of view, the second point is particularly relevant. Since the final size of the throughput of world economy will be achieved only when all countries reach the expected threshold level (admitting that this will be possible), only then will it be possible to determine the final size of the world's population.

To make things more difficult, two additional explanations should be added to three presented above for explaining the dematerialization of developed countries shown be historic series.

The first explanation is linked to the idea of 'trans-materialization'— the idea that the economy of many developed countries uses 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, therefore, EKCs simply "do not see" what is going on in reality.

The second explanation also illustrates the deficiency of using EKC in representing the phenomenon. More and more in the last decades a certain fraction of the economic activities required for sustaining the societal metabolism of developed countries, especially the most energy- and resource-intensive sectors, have been shifted to developing countries. In this case, we simply deal with an externalization of the phase of possible re-materialization 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 dematerialization, but just an artifact generated by a sort of "epistemological cheating." Damages to the environment due to "externalized economic activities" simply do not show up in analyses made at the national level.

In conclusion, even admitting that some countries are in a dematerialization phase (as shown by Jänicke et al., 1989), the entire debate may remain sterile, as noted by De Bruyn and Opschoor (1997). In fact, some developed countries are in a re-materialization phase, after experiencing a phase of dematerialization during the previous years. This, "re-linking hypothesis" implies that an inversion in existing trends could always occur even for those countries that at the moment are still in a de-linking stage. According to this hypothesis, the curve of the throughput versus GNP per capita, would therefore not follow the inverted-U shaped curve, but rather an N-shaped one. That is, the N-shaped curve implies 3 phases: (1) The use of resources grows in parallel with income growth; (2) This phase of capitalization is followed by a reduction in the rate of materialization in which the major increase in output is in the service sector; (3) At this point a new materialization phase can start at any moment when new activities are introduced in the economic process. This phase will continue until new technological innovations (increase in the efficiency for the new activities) allow for a new de-linking.

As noted above, there is empirical support for this alternative hypothesis. This challenges the traditional theories of the relationships among the economy, energy, and the environment. The following empirical conventional analysis of changes in Spain adds to the available data on these relationships.

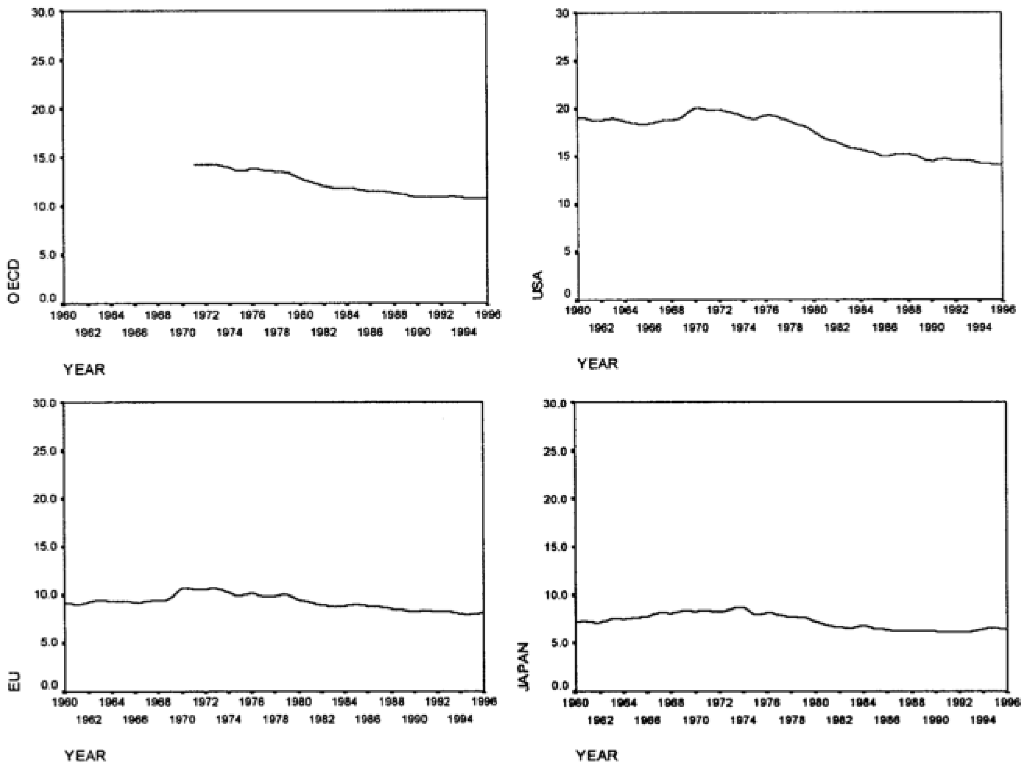
The Empirical Data on Changes in Energy Intensity of Spain

This analysis is focused only on the relationship between GDP and the consumption of commercial energy, considered as a proxy of an intensive indicator of throughput. The variable 'energy intensity' is defined as "Total Primary Energy Supply" divided by GDP, and is expressed in MJ/US90$ (1 MJ = 10^6 joules).

A set of countries following the hypothesis of dematerialization is shown in Figure 1. This figure shows how energy intensity in the OECD, USA, Japan, and EU has been decreasing in the period from 1960 to 1996. These curves can be used for a comparison with Spain.

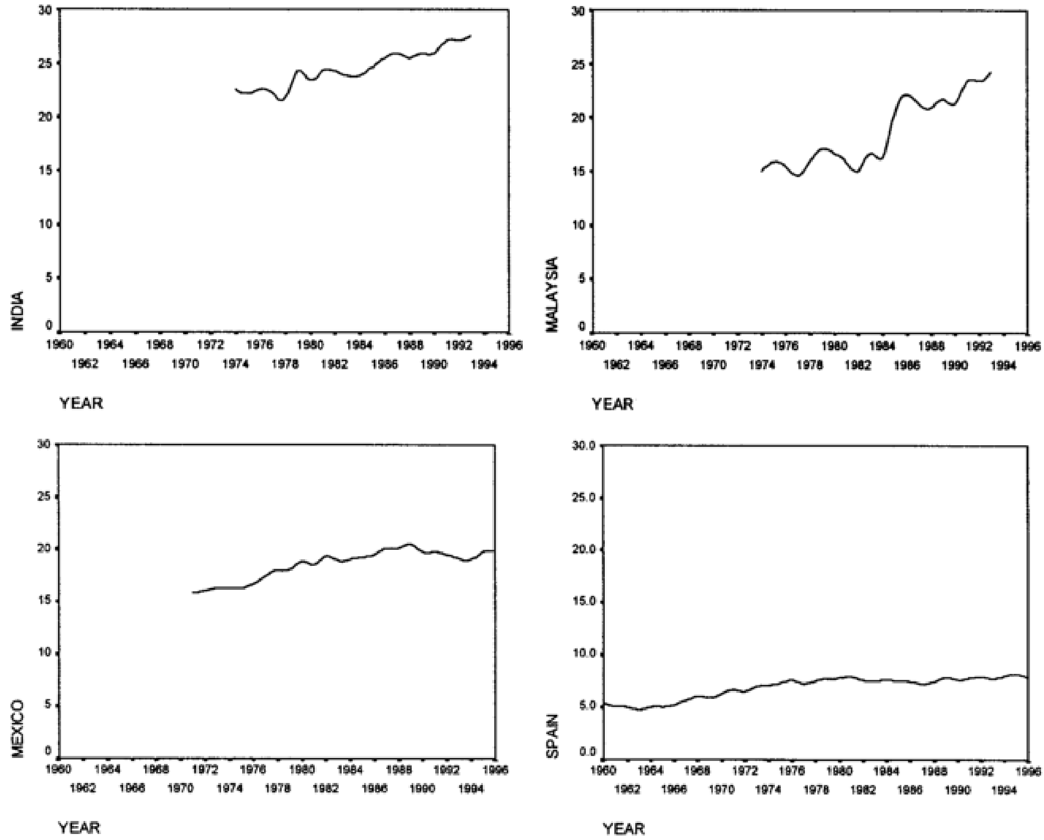
As expected according to the theory, India, Malaysia, and Mexico, three developing countries, show growing energy intensities when analyzed over the last 30 years. (See Figure 2.) According to the hypothesis, these developing countries are still increasing their energy intensity since they did not reach the "threshold value" yet. However, the problem comes with the curve of Spain (the lower curve in Figure 2). This curve also shows a continuous growth in this variable over the same time window considered for the other OECD countries in Figure 1.

Figure 1. Energy intensity for the OECD, the USA, the EU, and Japan in MJ/US90$.



Two points from the graph of Spain in Figure 2 deserve attention. First, the Spanish economy is increasing its energy intensity over time. Second, this tendency is not continuous. In fact, we can see how energy intensity increased very quickly from 1963 to 1981 (from 4.7 to 7.9 MJ/US90$) and remained around the value of 7.8 MJ/US90$ with moderate ups and downs until 1996. Therefore, according to this graph, we can say that Spain does not follow the hypothesis of the inverted-U shaped curve.

Figure 2. Energy intensity for India, Malaysia, Mexico, and Spain in MJ/US90$

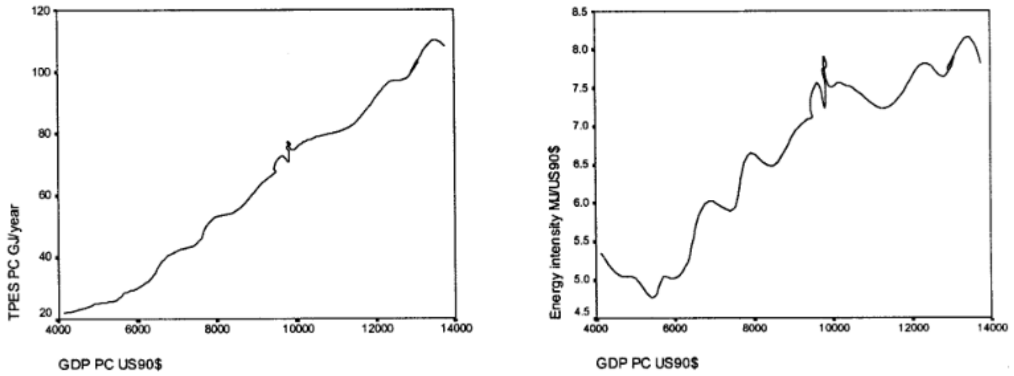


However, one might argue that this is due to the fact that Spain has not yet reached the inflection point or the 'peak' year. Put another way, the economy of Spain is still not developed enough to start dematerializing. This objection can be rejected easily. As it is shown by Unruh and Moomaw (1998, p.225), the majority of developed countries following the EKC hypothesis show their peak year for energy intensity in the 1970s. This year is linked to values of GDP per capita in the range between 9,000 US$ (Austria on the lower side) and 15,500 US$ (USA on the higher side). The majority of countries reach the point of inflection at a value of about 11,000 US$ GDP per capita.

Spain is far from being a fuel-based economy like the USA or Canada and should therefore show a behavior more similar to Austria. However, Spain still shows a growing energy intensity in 1996 after having surpassed the13,500 US$ of GDP per capita. If the hypothesis were true, Spain should have shown signs of dematerialization much earlier.

The same result is obtained if we graph the relationship between the indicator of throughput per capita (TPES per capita) and the GDP per capita (the famous EKC), or the energy intensity and the GDP per capita. These two curves are shown in Figure 3. The graphs shown in Figure 3 confirm what may already be seen in Figure 2: Spain has not reached the peak year and the evolution of energy intensity is not continuous, but with ups and downs.

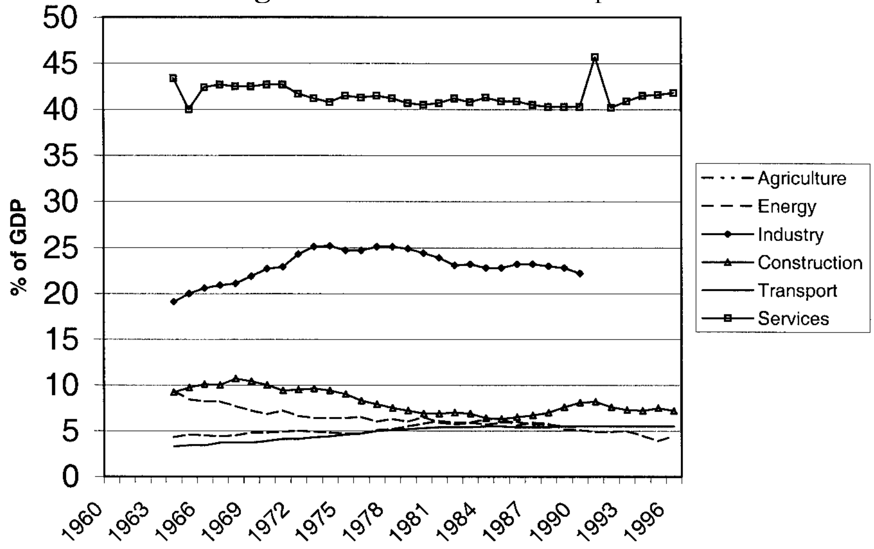
Figure 3. The Environmental Kuznets Curves for Spain, A = Total primary energy supply per capita in Gj/year; B = Energy intensity in Mj/$.



Possible Explanations of these Changes by Looking at Sectorial Changes

Some authors (Simonis, 1989; Jänicke et al., 1989, cited in De Bruyn & Opschoor 1997) state that technological and institutional change, or generically "structural change" (that includes changes in consumption patterns), are the main causes of the evolution of energy intensity. This proposal accounts for the fact that after the first oil crisis in the early 1970s, the energy intensity in Spain grew rather than decreased as in other developed countries. On that occasion, the Spanish government (following the advice of the IMF) compensated the rising prices with subventions, postponing the adaptation of the economy to higher prices. However, after the second oil crisis in the late 1970s, the intensity of some economic sectors finally decreased for two reasons: (1) The government did not again resort to subventions, allowing increases in prices. This fact made energy, a production factor, more expensive not only in absolute terms but also relatively when compared with capital or labor. Thus, most industries adapted to the new situation, improved efficiency, and changed the mix of fuels. (2) A deep industrial restructuring, which started in the early 1980s, implied closing down many traditional factories with high energy consumption levels, such as shipyards and steelworks.

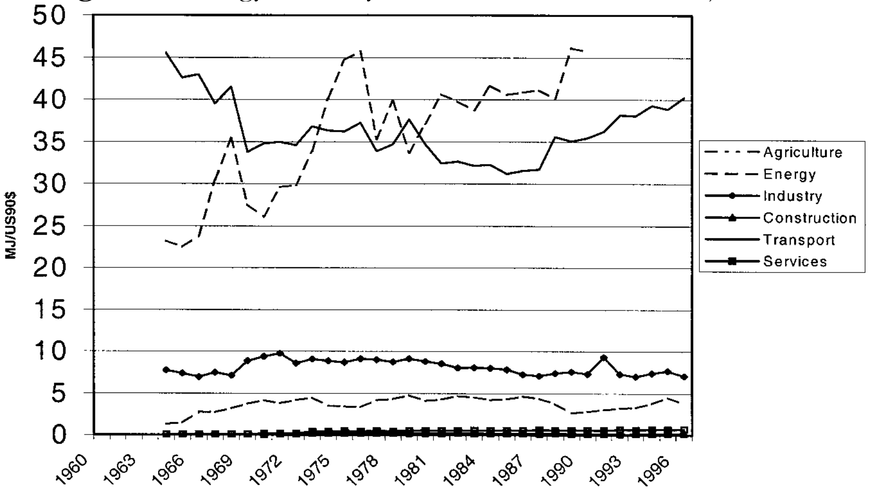
Figure 4. GDP structure in Spain.



This is the main factor that seems to explain the changes in Spanish evolution. That is, local decreases in the variable "energy intensity" were reflecting structural changes (i.e., the economic restructuring mentioned above) rather than a smooth change in the evolution of the energy intensity.

Indeed, in the case of agriculture and construction, the energy intensity (Figure 5) has been more or less stable after the increase of the 1960s, whereas the relative importance of the sectors (as a percentage of the total GDP) has decreased over time (Figure 4). The industrial sector shows a similar evolution (Figures 4 and 5), in which its contribution to GDP has been decreasing since 1973. The industrial sector has also shown a decline in energy intensity since 1973, although the decline has not been continuous. The exception was 1991 when the increase in energy intensity resulted largely from the preparation for the Barcelona Olympic Games and for Seville's Universal Exhibition of the following year. This evolution is similar to that of some other developed countries that are shifting from industry to services.

Figure 5. Energy intensity in the different sectors, Mj/US90$.



However, the service sector has not grown very much (except in the year 1991 because of the events mentioned above). The energy sector grew only until 1980. The transport sector grew very quickly and now is about 5.5% of GDP (Figure 4). All of the three sectors show, with some differences, growing tendencies in energy intensity. This fact is especially relevant for the service sector, due to its size.

These data indicate that Spain is shifting its economic activity to the service sector, but at the same time that sector is increasing its energy intensity. This tends to compensate for the reduction of energy intensity in industry and to increase the overall energy intensity of the economy.

Finally, an additional explanation of the peculiar evolution of the energy intensity of Spain is that the country has not yet shifted matter and energy intensive industries to the developing world, as some other developed countries that follow the inverted-U shaped curve have done. However, in order to check this hypothesis, we should have available data on the evolution of both the international trade and the internal consumption of these intensive goods, something that I leave for another paper.

The Evolutionary Analysis Based on a Phase Diagram

This section presents an alternative approach to deal with the study of energy metabolism of societies. This approach is used to investigate two relevant points that emerged in the analysis presented before: (1) The hypothesis of dematerialization does not apply to Spain (nor does the EKC); (2) Changes in energy intensity do not follow a continuous smooth curve.

The Perspective of Dynamic Systems

The hypothesis of dematerialization considers the implications of the principle of matter-energy conservation, but seems to ignore the implications of other characteristics of complex adaptive systems. Human society (and its subsystems) may be conceptualized as a complex adaptive system (Giampietro, 1997, p. 83). It is also a hierarchical system operating on different space-time scales. For example, changes in cultural identity, institutional changes, technological change and changes in individual preferences occur in parallel, but with different frequencies.

This implies that when proposing future scenarios reflecting changes occurring now, we should base our analysis not on the ceteris paribus hypothesis but rather on characteristics reflecting the evolutionary nature of the system. This is very important since the studies that forecast dematerialization are based on extrapolation of historical patterns into the future. Before using this type of analysis to recommend policies for the future one should, first of all, check whether the patterns that occurred in the past (e.g., past trajectories of dematerialization) can be expected to be repeated in the future or not. This implies using a time scale able to recognize historical patterns for use in extrapolation into the future.

As stated half a century ago by Schumpeter (1949, p. 58), "it is not possible to explain economic change by previous economic conditions alone" (emphasis in the original). One factor, which supports this warning against unwarranted extrapolation, is that efficiency implies a faster processing of information and knowledge. This leads, then, to a faster potential depletion of resources (more energy consumption fueling an enlarged set of activities). This is the so-called Jevons' paradox (Jevons, 1990). Jevons' paradox (also called the 'rebound effect,' or 'Khazzoom-Brookes' postulate) states that an increase in efficiency in using a resource leads, in the long term, to an increased use of that resource rather than to a reduction (Giampietro & Mayumi, 2000). In the case of energy, it implies that a promotion of energy efficiency at the micro-level (individual economic agents) might increase energy consumption at the macro-level (whole society) (Herring, 1999).

There are two relevant aspects to be considered here. One is the fact, well-known in economics, that improvements in efficiency lead to cheaper resources, thereby encouraging their use. The second is the fact that societies, as complex systems, work at different hierarchical levels. Changes defined at one level (i.e., efficiency in the use of energy at home) cannot be extrapolated to upper hierarchical levels (i.e., total energy consumption in the whole societies) because of the numerous feed-backs and relationships that are operating across these levels (see Giampietro & Mayumi, and Pastore et al., this issue).

This paradox, which holds in economic theory, has been tested many times. For example, Giampietro (1994) shows how "doubling the efficiency of food production per hectare over the last 50 years, due to a dramatic increase in "efficiency" . . . did not solve the problem of hunger[;] it actually made it worse, since it increased the number of people requiring food." Another example is proposed by Herring (1999) who reports that increases in lamp efficiency in public lighting in the UK took the form of a higher level of service, both in more miles illuminated and in higher illumination levels. Increased efficiency resulted in higher consumption.

Increasing the efficiency of a process only implies improvements in intensive variables. This will lead to effective savings in resources, only if the system does not adjust to this imposed change, by increasing consumption. Increases in efficiency can be used either to lower the stress of ecosystems (producing the same goods and services with fewer resources) or to produce more goods and services while maintaining the same level of stress (Giampietro & Mayumi, 2000). The latter solution is typical of human systems. Therefore, we can expect that in response to increases in efficiency, humans will increase their level of activity or even introduce new activities that before could not be afforded. The conclusion is that we can be more energy efficient but still consume more energy!

This idea might explain the ups and downs of energy intensity for Spain. That is, the results of "improvements in efficiency" can induce oscillations (decreases of consumption at one level followed by increases in consumption at a different level) in energy intensity.

Another relevant aspect of human systems (i.e., individuals, households, whole economies) is that they are 'dissipative systems.' When describing them in biophysical terms, we can say that they are open systems not in thermodynamic equilibrium. These systems maintain their internal organization by constantly consuming energy carriers (food in the case of humans and fossil fuels in the case of economies). The very concept of societal metabolism implies that the economic process can be described in biophysical terms as the stabilization of matter-energy flows linked to the production and consumption of goods and services. Dissipative complex systems interact both with the environment and with each other by continuously adapting to new circumstances. That is they co-evolve with their context. Due to the necessity of this continuous interaction and adaptation, it is impossible to expect that these systems will operate successfully when having access only to a single state of equilibrium for their societal energy budget. Instead, the most probable solution is that they have accessible a set of possible points of dynamic equilibrium.

Representing Changes in Energy Intensity on a Phase Diagram

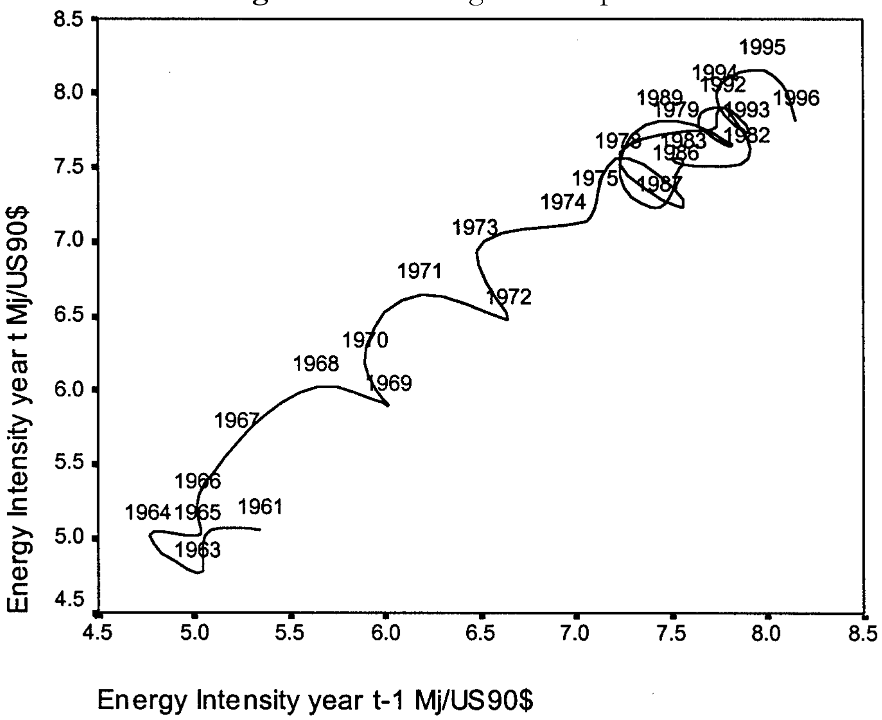
According to the discussion in the previous section, it is difficult to describe societal metabolism by adopting traditional linear techniques. Non-linear dynamic techniques allow us to observe patterns of temporal behavior and intermittent changes in the set of considered variables.

For example, Gowdy (1994) applies to the economy the vision, originating in paleontology, of evolution as a 'punctuated equilibrium' (Eldridge & Gould, 1972). This is the new name for something that was studied before by Schumpeter, who saw development as "spontaneous and discontinuous changes in the channels of the flow, disturbance of equilibrium, which forever alters and displaces the equilibrium state previously existing" (Schumpeter, 1949, p. 64). That is, economic systems might stay in a stable phase, in which the parameters of the dynamic equilibrium of their energy budget move around attractor points. These stable phases can be followed by radical changes in the technological paradigm and in the industrial structure. This can be seen as the movement to a different attractor point, which provides stability to the dynamic equilibrium, but in a different area of the viability domain. The development of societies would then go from one attractor point to the next or, using Schumpeter's words (1949, p. 66), they would be "carrying out new combinations" of structural and institutional changes.

One way of analyzing the existence of this discontinuity is by means of a phase diagram. This methodology has been used in the case of CO2 emissions (Unruh & Moomaw, 1998), and in the case of energy intensity (De Bruyn, 1999).

The phase diagram for energy intensity for Spain is shown in Figure 6. The Y-axis represents the energy intensity in the year t (expressed in MJ/US90$), and the X-axis represents the same variable in the year $t - 1$. The various points obtained in this way are then joined by drawing a line. If the increase in energy intensity observed in Figure 2 would be due to gradual changes in intensity of use (as claimed by the original hypothesis of the intensity of use), then the phase diagram in Figure 6 should show a more or less straight positive line, implying greater intensities over time. However, if we are facing a situation of "punctuated equilibrium", the phase diagram should show different attractor points where the values taken by the variable "energy intensity" move around a given value. In the case of Spain, we can see clearly two different attractor points, one between 1960–1966, and the second between 1976–1996.

Figure 6. Phase diagram for Spain.



This second attractor point implies that values of energy intensity move around the value of 7.8 MJ/US90$. Between these two points, we can see a transitional period, which we would characterize as re-energization. This graph indicates that when considering its energy intensity, Spain is following the dynamic behavior described by De Bruyn (1999).

This behavior can be linked to the peculiarity of complex adaptive systems discussed above. Important feedback effects of energy dissipation across different hierarchical levels affecting the characteristics of the whole system translate into strong non-linearity.

Discussing the Insight Provided by the Dynamic/Evolutionary View

The phase diagram shown in Figure 6 shows that in the time period being considered the evolutionary trajectory of energy intensity went through phases of stability (when moving around the two attractor points) and a transitional phase (when moving from one attractor to the other). The values taken by the variable "energy intensity" are stagnant around attractor points, and increasing rapidly in the transitional phase.

Unlike the pattern of reductions in energy intensity found in other developed countries, the overall trend for energy intensity in Spain increased during the period under consideration. This implies that structural and/or institutional changes in Spain did not generate the same reduction in energy intensity as occurred in other developed countries. But to better understand this peculiarity, we have to distinguish between analyses of the evolutionary trajectory performed on different scales. On a medium scale, structural changes can bring a period of stability (generating a new attractor point). This gives the impression of stability and a well-established trend toward de-materialization. On the other hand, when using a larger time window, we can appreciate the trajectory across different attractor points. In this case, when considering the various transitional phases in the movement across different attractor points, it is the relative position of the various attractor points that will determine the overall trend.

To understand the mechanisms generating these changes on different levels (and at different scales) implies studying in parallel the evolution of the energy metabolism of the whole country and that of different sectors of the economy. When this is done in the case of Spain, crucial role of changes that are still occurring in the household sector (i.e., in the demand side of the economy) becomes evident.

Finally, before closing this analysis of the implications of the evolutionary perspective, I have to re-iterate two points crucial for this analysis: (1) Intensive variables (i.e., energy intensity—MJ/$) are useful to describe changes in relevant qualities of societal metabolism. However, they are not enough, since they do not reflect the evolution of the throughput and its environmental impact. We need to use in parallel additional variables reflecting the absolute evolution of the throughput (e.g., what is the final value of MJ when we calculate the product "MJ/$ of GDP" × "$ of GDP per capita").

(2) The existence of feed-backs between different hierarchical levels of a complex adaptive system implies that we cannot make a linear extrapolation of a trend observed at one level to another trend at a different level. In these cases, we have to address the dynamic nature of the system by using new tools, such as phase diagrams, to represent the non-linear behavior of the variables considered. Equally useful is the parallel analysis of changes on different scales and the study of their reciprocal effect.

Integrated Assessment of Exosomatic Metabolism Across Levels

In this section I introduce the approach of integrated assessment of the exosomatic metabolic rates of economic compartments presented by Giampietro and Mayumi (two papers in this issue) and used by Falconí (this issue). An integrated analysis implies that the economic development and energy metabolism of societies are described in parallel using economic variables and biophysical units across different hierarchical levels. Examples of economic variables and biophysical units include human time allocation and energy consumption.

With this analysis I explore the same issues explored in Section 2 using only economic variables. Here I use additional variables and a different perspective, resulting in different interpretations. In this way, I hope to show to the reader that the analysis is more robust and more useful.

This section has the two goals: (1) The analysis will provide additional explanations for the peculiar behavior of Spain, a developed country with an increasing energy intensity. To do that I explain the role of the different sectors in determining the overall increase of energy intensity over time. In particular, this analysis points at the special role plaid by the household sector. (2) This analysis also provides explanations of the mechanism generating Spain's development trajectory. The combined effects of the characteristics of its societal metabolism (changes in endosomatic flows linked to demographic variables and changes in exosomatic flows linked to economic variables) imply that Spain, in contrast to the case of Ecuador presented by Falconí (this issue) was characterized by a positive spiral of development. This leads to an increase in capitalization of its various compartments, especially the household sector. Before presenting this analysis, I provide some definitions of the relations used in the next section.

The relations Used in the Analysis

The parameters used are those presented and discussed in Appendix 1 and Appendix 2 of the paper of Giampietro and Mayumi (second paper of this issue). For purposes of this analysis, the economy of Spain has been divided into two main sectors: the paid work sector (PW) and the household sector (HH). The paid work sector of the economy is the one that generates added value (or GDP), and the household sector of the economy is the one that consumes that value. Both of them, however, consume energy for their maintenance and development. The paid work sector can be divided into three major sub-sectors, the productive sector (PS), services and government (SG), and agriculture (AG).

$PW = PS + SG + AG$ Relation 1

Energy intensity (EI) is total energy consumption, or total energy throughput (TET) divided by Gross Domestic Product, and, in this study, it is measured in MJ/US90$.

$EI = TET / GDP$ Relation 2

Some useful ratios that will be used later are defined as follows: The average exosomatic metabolic rate of the society (EMR_{AS}) is the total exosomatic energy throughput (TET) divided by the total human time (THA) of the society. This ratio gives us the rate of energy use of the society in megajoules (MJ) per hour. This is an intensive variable that reflects the rate at which society dissipates energy for its maintenance and development per unit of human activity.

$EMR_{AS} = TET / THA$ Relation 3

By analogy, we can derive the same kind of ratio in the case of the household sector and the paid work sector. That is,

$EMR_{HH} = ET_{HH} / HA_{HH}$ Relation 4

In this relation, ET_{HH} is the energy consumption in the household sector and HA_{HH} is the non-working human time in the society. (For calculation of this, see Giampietro and Mayumi [second paper of this issue].) In this study ET_{HH} is calculated as residential energy consumption plus 50% of transport energy consumption. This later assumption is derived from the average energy consumption of cars and the number of circulating cars. This suggests that 50% of energy used in the transport sector can be attributed to households. (See assessments and data source in the Appendix.) The other 50% of energy in the transport sector can be allocated to the services and government sector. In fact, even if this is used to carry items used by manufacturing, this transport will generate an added value within the service sector.

An increase in EMR_{HH} reflects an increase in the standard of living (see Pastore et al., this issue) and a higher capitalization and consumption in the HH sector.

By using the same procedure used in relation (3) and (4) we have:

$EMR_{PW} = ET_{PW} / HA_{PW}$ Relation 5

In this relation ET_{PW} is the energy consumption in the sectors that generate added value, and HA_{PW} is the human working time. (I use a flat value of 1,840 hours per year for employed people.) As discussed below, EMR_{PW} can be taken as a proxy for investments in the PW sector. The same holds for EMR_{PS}, EMR_{SG}, and EMR_{AG}.

The last ratio used in this analysis is the economic labor productivity (ELP) that can be defined as GDP / HA_{PW} in dollars per hour. Again, we can also calculate ELP_{AG}, ELP_{PS}, and ELP_{SG} by dividing a sectorial GDP by its relative amount of working time in hours. For example, when using the economic reading, we can define TET = EI* GDP (from Relation 2), but from this integrated assessment, due to the fact that $HA = HA_{HH} + HA_{PW}$, and $TET = ET_{HH} + ET_{PW}$, we can define TET as follows,

$$TET = (HA_{HH} * EMR_{HH}) + (HA_{PW} * EMR_{PW}) \qquad \text{Relation 6}$$

Using data for 1990, in the case of Spain, we obtain:

$$TET = EI * GDP = (HA_{HH} * EMR_{HH}) + (HA_{PW} * EMR_{PW})$$

3.79*10^12 MJ = 7.65 MJ/$ * 494.794*10^9 $ = (3.17*10^11h * 2.72 MJ/h) + (2.32*10^10h * 125.89 MJ/h) = 3.79*10^12 MJ

We can do the same for ET_{PW}. From Relation 1 we know that PW = PS + SG + AG. We can therefore define ET_{PW} as follows,

$$ET_{PW} = (HA_{PS} * EMR_{PS}) + (HA_{SG} * EMR_{SG}) + (HA_{AG} * EMR_{AG}) \qquad \text{Relation 7}$$

Again, when using Spanish data for 1990, the previous identity becomes:

ET_{PW} = 2.92*10^12 MJ = (7.74*10^9 h * 287.55 MJ/h) + (1.29*10^10 h * 48.66 MJ/h) + (2.61*10^9h * 26.99 MJ/h) = 2.92*10^12 MJ

For a discussion of the usefulness of writing identities containing redundant information that can be retrieved by using non-equivalent data sources, see Giampietro and Mayumi (second paper of this issue). Briefly, these examples show that it is possible to define the same variable (i.e., TET or ET_{PW}), using an economic reading (energy intensity and GDP) or using an integrated assessment (using exosomatic metabolic rates and human time allocation referring to the characteristics of lower hierarchical levels). This gives our analysis a wider scope and more robustness, and allows us to give different explanations to the same facts.

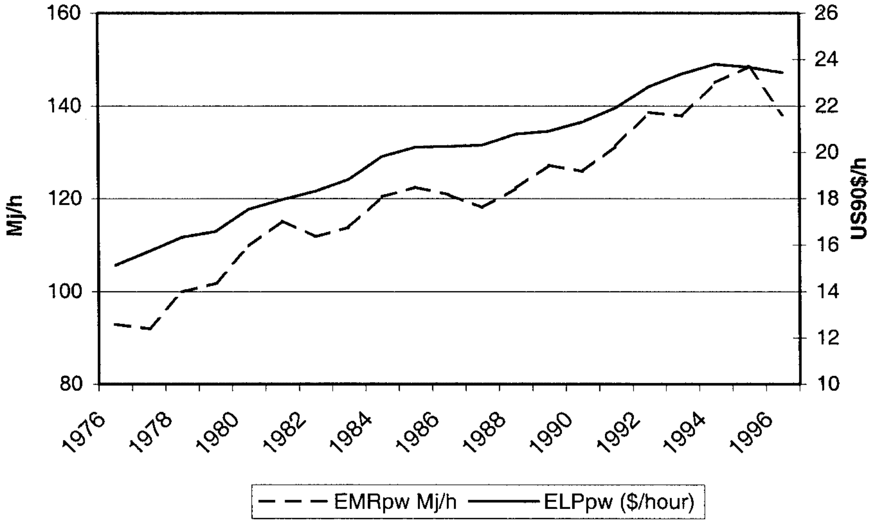
Describing Changes of ELP and EMR in the Various Sectors

The various data sources and methods for calculating the figures presented in this section are given in the Appendix. By calculating these ratios for Spanish economy, we obtain important information that would be lost otherwise.

Integrated assessment reveals the association between the capitalization of productive sectors (assessed by their exosomatic energy consumption = fixed plus circulating) and their ability to produce GDP. This hypothesis implies that EMR_{PW} and ELP_{PW} are correlated (Cleveland et al., 1984; Hall et al., 1986). The robust correlation obtained by Cleveland et al. (1984) in their historic analysis of the US economy is confirmed by the curves shown in Figure 7 for Spain. When representing changes of EMR_{PW} and ELP_{PW} we find a similar shape or tendency in the considered period. That is, exosomatic energy consumption per unit of working time in the paid work sector follows the GDP trend. The same finding has been obtained in the historic analysis of Ecuador (see Figure 6 in Falconí, this issue).

If we accept the validity of this correlation during the considered time window, it follows that changes in the energy intensity of Spain are generated by: (1) differences in the speed at which the two parameters EMR and ELP adjust in relation to each other; and (2) changes occurring outside the paid work sector. This second option points at the possibility that important changes in Spain are taking place in the household sector.

Figure 7. Exosomatic Metabolic Rate and Economic Labour Productivity in paid work sectors.



Changes in the PW Sector. The EMR_{PW} increased from 92.92 MJ/hour in 1976 to 138.13 MJ/hour in 1996. This reflects the accumulation of capital in the sectors of the economy producing added value. This change has been reflected in a relative increase in the economic productivity of labor (ELP_{PW}) (from 15.3 $/hour in 1976 to 23.4 in 1996). As a side effect, this allowed the relative decrease of the human time allocated in activities that generate added value. In fact, more exosomatic energy used per worker implies the existence of more exosomatic devices per worker (technology) linked to the ability to buy more oil to perform the given economic activity. The two things, fixed investment—the exosomatic devices needed to dissipate fossil energy in an useful way by workers, and circulating investment—fossil energy consumed, combined together are an indicator of a larger capitalization of the economic activity considered. That is, an increase in EMR leading to an increase in ELP is linked to more technology involved in production.

Changes in the HH Sector. If the changes in the PW sector led to an increase of non-working time, how was this reflected in the level of capitalization of the household sector? In the example of the analysis of Ecuador, Falconí (this issue) shows that a sharp increase in HA_{HH} translated into a sharp reduction of EMR_{HH} because the increase in ET_{HH} could not keep the pace of growth of HA_{HH}. However, contrary to what happened in Ecuador in the recent decades, the exosomatic metabolic rate of the household sector (EMR_{HH}) in Spain almost doubled. It went, from 1.67 MJ/hour in 1976 to 3.27 MJ/hour in 1996.

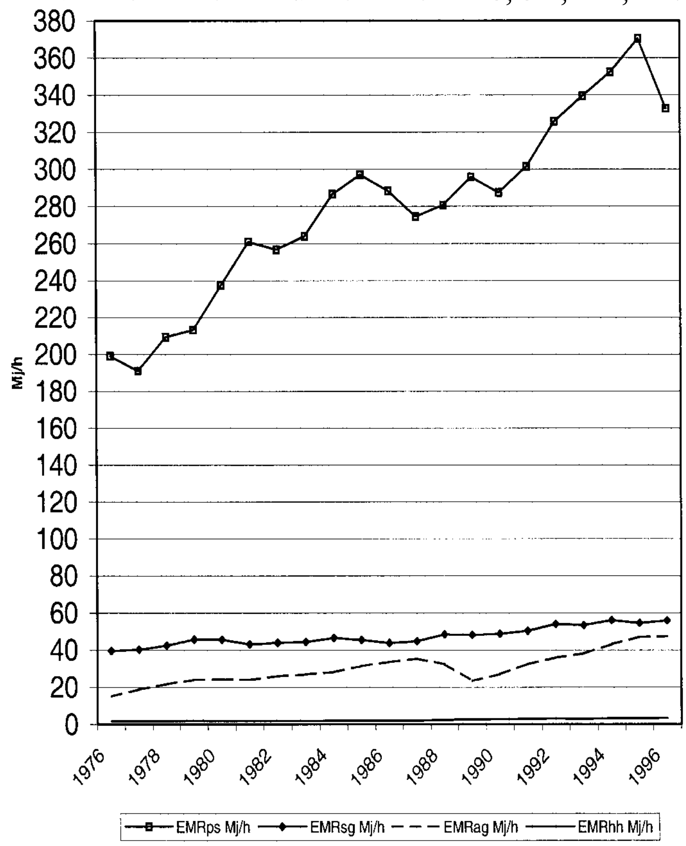
Combining the Two. When combining changes in intensive variables (EMRi) and extensive variables (HAi) and when considering sectors dealing with both production and consumption, we obtain a different picture of changes of energy intensity in Spain from that obtained in the first analysis. Even though industry is decreasing its energy intensity, the overall energy intensity of the economy is increasing due to the behavior of the household sector. The household sector is also increasing energy consumption in absolute terms, from 490 PJ in 1976 to 1,050 PJ in 1996 (1 PJ = 10^15 J).

This fact is usually neglected by the studies on the EKC or energy intensity that focus only in the supply side of the economy (= on changes in the paid work sectors). However, the demand side, the household sector, can be a relevant factor explaining the development of energy intensity, and should be carefully considered. This result, so important for policy generation, cannot be found when using the traditional approach. That is, using an analysis based on human time allocation provides new insights to the Spanish anomaly of an energy intensity increase.

The Crucial Role of Changes in Investments of HA among the Various Sectors

When representing the different exosomatic metabolic rates of the economy (Figure 8), we obtain important information. That figure shows that EMR_{PS} >> EMR_{SG} > EMR_{AG} > EMR_{HH}.

Figure 8. Exosomatic Metabolic Rates of PS, SG, AG, and HH.



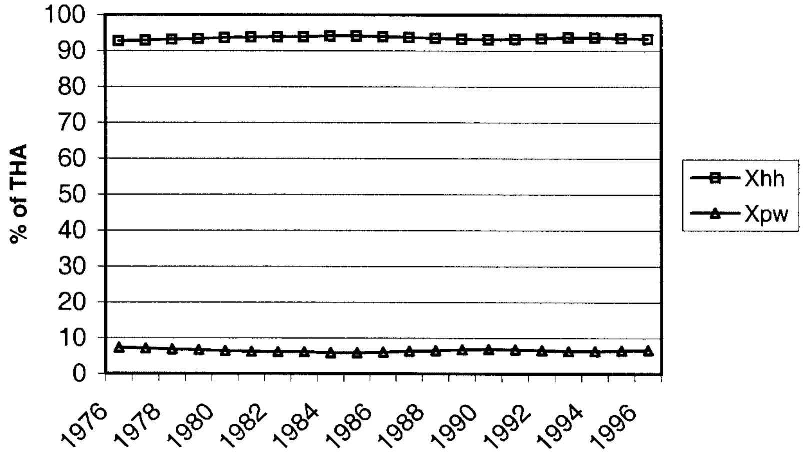
This sequence is very important since it implies when studying changes in the rate of consumption of exosomatic energy per capita in a country (EMR_{SA}), we have to look at the changes in the profile of human time allocation between these different sectors.

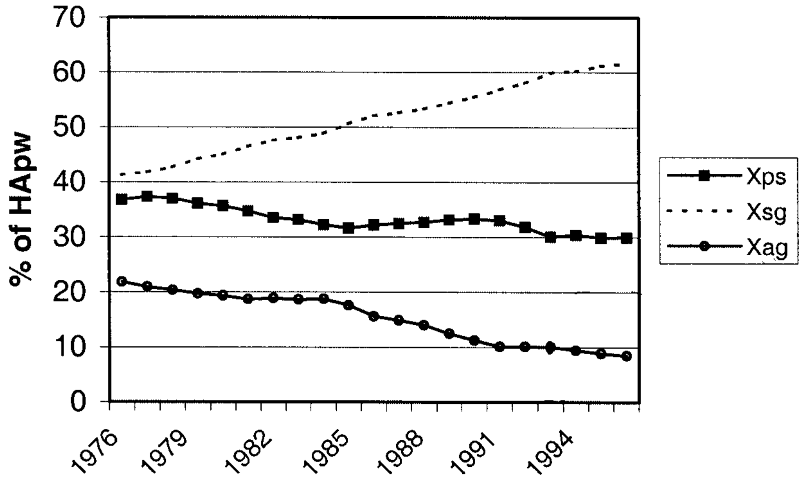
This is shown in Figure 9. In the upper part (A) we find that both HA_{HH} and HA_{PW} maintain approximately the same percentage of THA over the time window considered. In the lower part of Figure 9 (B) we can see the evolution of different values of HAi as a percentage of HA_{PW}, a variable that we call Xi.

The real value of EMR_{PW} and therefore its curve in time not only depends on level of capitalization and technological efficiency of each one of the various sectors (the value take by EMRi), but it also depends on the profile of distribution of "working time" over the three different sectors, PS, SG, and AG. The percentage of working time in PS and AG is decreasing, while the same percentage of SG is increasing. This is associated with the post-industrialization of the economy.

When combining this result with the relative value of the different EMRi considered, we can conclude that the decrease in energy intensity in PS has been offset by: (1) an increase in EMR_{SG} linked to a growing size of the SG sector, and (2) the increase in EMR_{HH} occurring in a sector which is much larger than the others (see Figure 9 A). That is, to explain the overall increase in energy intensity of Spain we have to combine (using extensive and intensive variables) different changes in the characteristics of the various sectors.

Figure 9. Distribution of working time between sectors. A: HA_{pw} and HA_{hh} as a % of THA; B: HA_{ps}, HA_{sg}, and HA_{ag} as % of HA_{pw}.





The Dynamics Associated to Economic Development

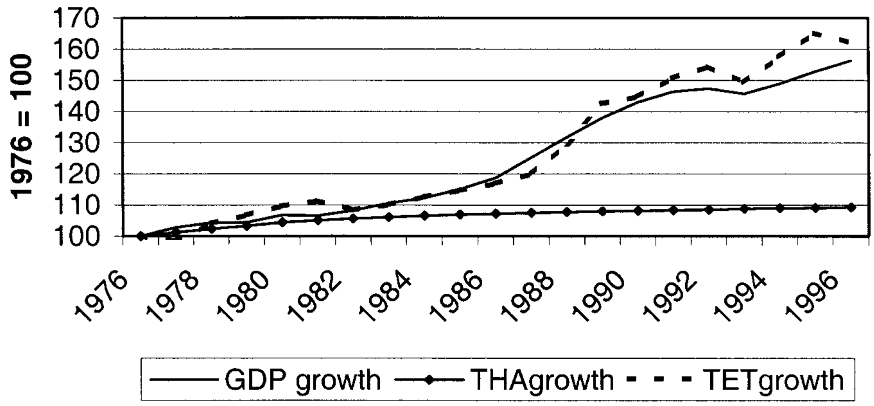
The relation between EMR_{PW} and ELP_{PW} would indicate that there is a quantitative link between GDP and energy consumption growth. However, the growth of total economic output can be explained by: (1) rate of population increase (dTHA/dt); (2) rise in the material standard of living ($dEMR_{HH}/dt$); or (3) increase in the capitalization of economic sectors included in PW ($dEMR_{PW}/dt$). Whenever performance of the economy generates a surplus (an extra added value beyond what is used for its maintenance), this can be used to increase these three parameters.

What are the implications, then, of the link between EMR_{PW} and ELP_{PW}, shown in Figure 7? In order to have economic growth ET_{PW} has to grow faster than HA_{PW}. This will be reflected in an increase in EMR_{PW}, which will be influenced by a larger availability of investment for producing GDP. Clearly the priority among the possible end uses of available surpluses will depend on demographic variables, political choices (e.g., the ability and the willingness of compressing increases in the consumption of HH to favor quicker investments in PW), and historical circumstances (e.g., existing level of capitalization of the various sectors). The possible uses of available surpluses include (1) increasing THA, (2) increasing EMR_{HH}, or (3) increasing EMR_{PW}.

Contrary to the situation in Ecuador (see Falconí, this issue), the surplus generated by the economic development of Spain was enough to absorb both new population (due to internal demographic growth) and the exodus of workers from the agricultural sector. In fact, in recent decades Spain has still been absorbing a large fraction of workers moving away from the agricultural sector. This process of economic development was speeded up by a compression of the increases in material standard of living (increases in EMR_{HH})—under the Franco regime there were no free-unions. This made it possible to dedicate a larger fraction of this surplus to the capitalization of PW. Finally, the demographic stability of the country made it possible to enter a positive spiral very quickly.

The evolution in time of GDP, TET, and THA are shown in Figure 10. Again the curves of GDP and TET are very similar, confirming the hypothesis that EMR_{PW} and ELP_{PW} are correlated. In contrast, THA evolved toward a stagnation rather than an increase. This clearly indicates that the increase in the surplus was allocated either to increasing the capitalization of the economy (EMR_{PW}) or increasing the material standard of living (EMR_{HH}).

Figure 10. GDP, total human time and total energy consumption growth rates.



The very low levels of EMR_{HH} (when compared with those of other developed countries) indicate that in the early stages of industrial development Spain experienced a certain compression of consumption. However, once EMR_{PS} reached values comparable to those of other developed countries (i.e., 300 MJ/h) and the political situation changed, the surplus was allocated mainly to boost the SG sector (increasing X_{SG}, by absorbing workers from agriculture and increasing at the same time EMR_{SG}). The surplus was also allocated and to improve the material standard of living (by increasing EMR_{HH}). In particular, the capitalization of the Household sector implies the sharp increase in EMR observed previously.

When comparing the growth of EMR_{HH} and that of EMR_{PW} shown in Figure 11, we can actually see the lag-time reflecting the choices made in the process of economic development. Indeed, when Spain was still focusing on a rapid capitalization of the economy, EMR_{PW} was growing faster than EMR_{HH}. However, in the past 10 years, when the paid work sectors have been slowing, the growth rate, the increase in the material standard of living, and the increase in transport were the main factors responsible for the increase in consumption of energy. This resulted in the increase of energy intensity of Spain (see Figure 12).

Figure 11. Growth in Exosomatic Metabolic Rate (household sector and productive sectors) in Spain.

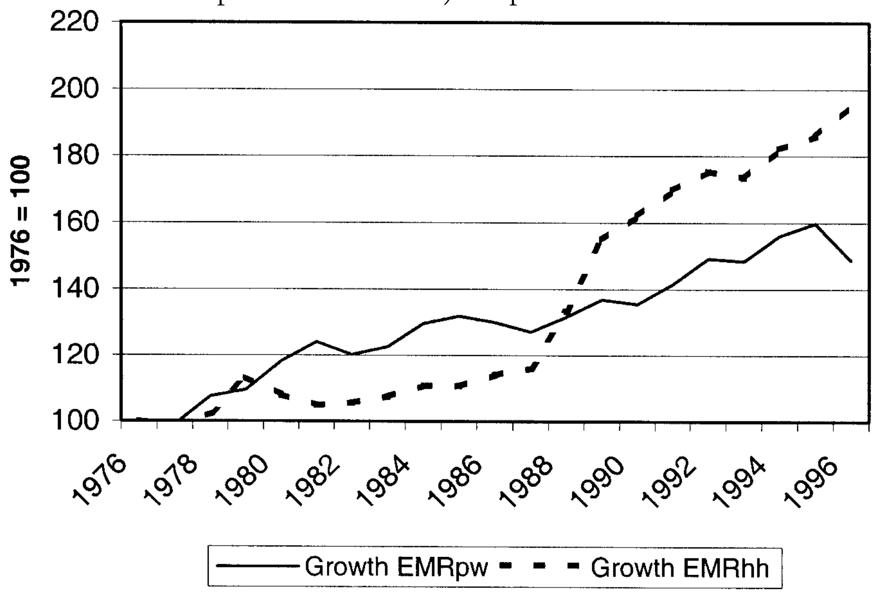
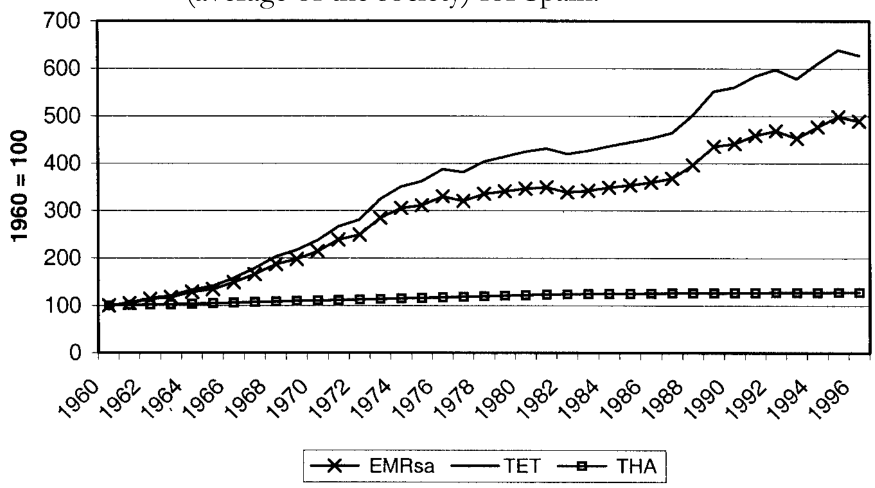


Figure 12. Population, Total Energy (TET), and Exosomatic Metabolic Rate (average of the society) for Spain.



When comparing this trajectory of development with that presented by Falconí for Ecuador, it can be said that in the case of Spain, low population growth and low debt service allowed the country to get into a positive spiral. Available surpluses were first invested to increase EMR_{PW} ($dET_{PW} > dHA_{PW}$). This led to an increase in ELP_{PW} that allowed the increase in the surplus (due to the temporary stagnation of EMR_{HH}). When a sufficient level of capitalization was reached in the PS sector (EMR_{PS} = 300 MJ/h), the surplus was allocated to expand the SG sector by absorbing the workers in AG with a reasonable amount of investment (since $EMR_{SG} < EMR_{PS}$) and to increase EMR_{HH}. It must be stressed that the dramatic difference in demographic trends between Spain and Ecuador is crucial to explain the different paths taken by Spain and Ecuador in their trajectories of development.

Conclusion

In this paper we have used three different approaches to the study of dematerialization of the Spanish economy. The first approach has been the conventional one, focusing on energy intensity and reflecting an economic reading. The second approach described the non-linear behavior of the energy intensity variable using a phase diagram. The third approach combined economic and biophysical variables when looking for explanation of the same pattern. The major results are as follows.

In Relation to Spain

Spain does not follow the intensity of use hypothesis of an inverted-U curve for energy intensity, since energy intensity is increasing over time. It follows therefore that the Environmental Kuznets Curve hypothesis does not hold for Spain.

The behavior of the energy intensity variable is not linear, but shows some ups and downs, jumping from one ‘attractor point’ to the next. Thus, changes in energy intensity are basically due to structural change (as explained in Section 3) and to the evolution of the characteristics of the various sector (especially HH), as discussed in section 4.

When considering the dynamic of economic development, Spain was able to take a different path than Ecuador thanks to the different characteristics of its energy budget. In particular low population growth was crucial in setting Spain’s trajectory into a positive spiral.

The increase in the level of capitalization of the household sector ($dEMR_{HH}/dt$) is one of the factors explaining the increase in energy intensity of Spain. Belonging to the demand side of the economy, this sector is usually not considered in conventional analyses of changes in energy intensity. On the contrary, this analysis shows that, when designing policies to reduce the environmental impact of the economy, we should take into account what is going on at the household sector. Changes in the set of activities linked to consumption can provide clues about the possibility of movements toward new attractor points—a perspective that fits well with the theory of punctuated equilibria).

In Relation to EKC and Other Hypotheses of De-materialization

The use of intensive variables, such as energy intensity, is certainly useful, for example, to choose between processes. However, this analysis is not sufficient to show whether the evolution is continuous or not. Moreover, it is also not relevant from an environmental point of view, because if we are interested in the metabolism of the society we have to look at the extensive variables that reflect behavior of the total throughput. For example, using the example of Spain, we can see in Figure 12 that the overall curve of TET is the result of changes in an intensive variable (the curve of EMR_{SA}) and an extensive variable (the curve of THA). From 1960 to 1996 population has grown from 30.5 million to 39.3 million (an increase of 28.7% for the period). During this same period, EMR_{SA} increased from 2.52 MJ/h to 12.32 MJ/h (a 388% increase for the period). Reflecting these changes TET went from 675 PJ to 4,240 PJ (a 528% for the period). Let’s imagine that this process of capitalization of the economy had occurred with a growth in population of 100% (as in the case of Ecuador considered by Falconí in his paper). It is when looking at these kinds of variables (mixing extensive and intensive) that we have an overview of the real throughput of the economy in relation to its possible environmental impact.

The existence of feedback between processes occurring at different hierarchical levels in complex adaptive systems implies that we cannot extrapolate results from one level to the other in a linear way. Therefore, we need different tools to represent the non-linear behavior of the variables considered. Paraphrasing Sun (1999), we can say that the EKC is only a reflection of our perception of the past development of the energy intensity (emphasis added). It is not a guide that tells us when a country is improving or not in environmental issues. Moreover, we can decrease energy intensity in any stage of development if we are willing to change the parameters determining the stability of the dynamic energy budget. We do not have to wait to reach some level of wealth.

The dematerialization hypothesis does not hold in conditions of continuous growth. As both the example of the Spanish economy presented here and the re-materialization phases found by De Bruyn and Opschoor (1997) indicate, developed countries can be on a trajectory of growth going across different attractor points. Rather than studying the trajectory followed when entering into the basin of attraction of a given attractor point (what is seen now by the curves "seeing" dematerialization), it would be more interesting to study what possible future attractor points we can imagine. This implies, that we cannot just wait for economic development to solve, by default, all our environmental problems. On the contrary, structural and institutional changes have to be sought in order to avoid both the re-materialization phases and the repetition of the same mistakes (or trends) by developing countries (getting into attractor points characterized by larger energy consumption).

A particular care has to be taken to avoid situations in which the dematerialization of developed countries is obtained by an over-materialization of developing countries. That is, we have to avoid the current trend toward the internationalization of environmental externalities. Mielnik and Goldemberg (1999) have shown this happening in the case of CO2. The developed countries included in Annex I to the Framework Convention on Climate Change would be 'de-carbonizing' in relation to their GDP, whilst the developing countries non included in Annex I would be 'carbonizing,' basically due to 'surrogate emissions' (Kopolo, 1999). Surrogate emissions in developing countries are generated by the production of goods and services consumed in the developed countries. Thus, international agreements and national governments should attempt to induce structural changes to avoid the tendency toward energy intensity as well as to reduce, later on, the metabolism of the system. This implies that the throughput of the economy should be compatible with several environmental thresholds besides being compatible with human expectations for a better standard of living. From a strictly environmental point of view, ecological constraints are independent of human wants.

Finally, the use of integrated models to characterize changes in economies based on the use of different variables to generate parallel descriptions of the same facts at different level seems to be essential when dealing with issue of sustainability. That is, when the effects of changes have to be assessed using different academic disciplines in parallel and in relation to events describable only on different levels. The generation of a "mosaic effect" among the various pieces of information improves the robustness of the analysis and the possibility of getting new insights generating synergism in the parallel use of different disciplines.

Appendix

Energy intensity has been calculated by dividing the Total Primary Energy Supply (TPES) expressed in joules by the Gross Domestic Product (GDP) expressed in 1990 US dollars, using the OECD data shown below.

The disaggregation by sectors for the Spanish economy has been done taking the disaggregated OECD data for energy consumption by sectors, as well as the aggregated GDP, and applying the evolution of the GDP structure by sectors found in the Spanish National Accounts in the reference list.

Data on population comes from the OECD, while data on employed people can be found on the Spanish National Statistics Institute web site http://www.ine.es. We assume 1840 hours for working time per year, that is 46 weeks times 40 hours per week. The distribution of the working time between the different sectors of the economy can also be found in the same web site.

When allocating the energy of the transport sector between the different sectors we make the following assumption: 50% of energy in the transport sector can be attributed to households. The other 50% can be allocated to the services and government sector. This later assumption is derived from the average energy consumption of cars and the number of circulating cars for developed countries, using the following sources:

1. "Transportation energy data book: edition 17," prepared by the Oak Ridge National Lab. (http://www-cta.ornl.gov/data/tedb17/tedb17.html).
2. "Transportation energy and the environment: Chapter 4", US Bureau of Transport Statistics (http://www.bts.gov/ntda/nts/NTS99/data/chapter4/content.pdf).
3. Statistical Compendium Europe's Environment from Eurostat (http://europa.eu.int/eurostat).

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