Can we use the energy intensity indicator to study "decoupling" and "dematerialization" in modern economies?

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Abstract

Energy intensity of an economy, defined as the ratio between the energy consumed and the Gross Domestic Product of a country, is a widely-adopted indicator of economic performance, often applied to sustainability analysis. The usefulness of this indicator has been challenged on the basis of the fact that the two variables making up this ratio are correlated. This implies that, when considered in isolation, each one of these two variables maps on to typologies of socio-economic systems (e.g. developed countries vs. less developed countries), however their ratio produces an indicator which does not map on to any meaningful typology of economic system (without an external referent). This paper checks the validity of this criticism by looking at the energy intensity of 133 countries over the period 1960-2009. Two approaches are used for this task: (1) an analysis at a given point in time (year 2009): after excluding countries with real GDPp.c.<5000US$ the paper considers three clusters of low, medium and high energy intensity countries. Within each cluster, when looking at similar values of EI, we find extremely diverse typologies of economies. (2) a video showing the movement in time of 133 countries between 1960 and 2010 over the plane determined by the two variables composing the indicator. These results seem to confirm the doubts about both the meaning and usefulness of the indicator itself. Rather than compressing non-equivalent indicators into a single number, quantitative assessments of the sustainability of modern economies should be based on a more complex combined use of variables and a multi-scale description across sectors and subsectors of the society.

Keywords: biophysical analysis of sustainability, dematerialization, decoupling, economic efficiency, energy intensity, PPP, societal metabolism

Introduction

The growing concern for the lack of sustainability of current trends of economic growth has primed, in the last two decades, an intense scientific discussion on the inadequacy of the conventional analytical tools used in the field (Sorman and Giampietro 2012, Kocsis 2012). In relation to this point, while it is becoming more and more clear that alternative pattern of economic development should be explored (van den Bergh 2010, Schneider et al. 2010, Nørgård 2012) it is also true that quantitative indicators used for analyzing the sustainability predicament are still based on the adoption of conventional economic narratives applied within a reductionistic framework – i.e. one scale and one dimension at the time (Giampietro et al. 2011). In relation to this point this papers wants to check the soundness of the Energy Intensity (EI) indicator, when applied at the country level, to study the effect of technological changes on the sustainability of modern economies. This indicator has been chosen because of its popularity in sustainability science, especially in relation to the hot issue of CO_2 emissions associated with climate change.

The article is structured as follows: Section 1 provides a brief overview of the EI indicator and the main critiques to its use (the two variables forming the energy intensity indicators - energy use and GDP - are highly correlated); Section 2 presents the empirical analysis obtained by calculating the indicator for 133 countries over the period 1960-2010. By using both a synchronic and a diachronic analysis of the two variables making up the indicator (energy use and GDP) on a plane it is possible to see that: (i) countries with extremely different economies do express the same value of energy intensity; (ii) the value of energy intensity of most countries evolves on a straight line over time, because of the high correlation between the two variables; Section 3 discusses the results; Section 4 gives the conclusions.

1. The popularity of the "energy intensity indicator" in sustainability analysis and the reasons for concern

1.1 Energy intensity as a tool to study sustainability

Energy intensity (EI) of an economy, defined as the energy needed to produce one unit of gross domestic product, is generally expressed as the ratio between primary energy consumption (e.g. tons of oil equivalent or MJ of Gross Energy Requirement) and the GDP (e.g. international - purchasing power parity - real dollars). The EI indicator is widely-adopted to assess both economic and sustainability performance of countries despite the existing criticism about the validity of such an indicator.

In relation to the energetic assessment, in the 70s and 80s many studies pointed out that differences in the quality of the mix of Primary Energy Sources (PES) and in the mix of Energy

Carriers (EC) used in an economy can explain the differences in the value of Energy Intensity (for an overview see Ayres et al. 2003; Ayres and Warr, 2005; Cleveland et al. 1984; Hall et al. 1986). More recent research (Duro and Padilla 2011) pointed to the role played by the mix of energy transformations and consumption structures to explain differences in EI across countries.

In relation to the economic assessment in 2003, Smil (2003) demonstrated that large inter-country differences in energy intensity tend to disappear when output is measured on a purchasing-power-parity basis. In conclusion, according to Liddle (2010) four main factors explain EI differences across countries: economic structure (energy-intensive industries share in total output), sectoral composition of energy use (shares of different end-uses like industry, buildings, and transport), fuel mix and efficiency in the end-use energy conversion.

However, in spite of this solid warning about the weakness of the EI indicator to study the effect of technological changes in the economy on its efficiency (defined as the consumption of primary energy per unit of added value), this indicator is still used in studies looking for proofs of “dematerialization” or “decoupling” due to technological progress (Goldemberg and Siqueira Prado 2011, UNEP 2011).

This paper does not want to get into a theoretical discussion over the validity of this indicator as done in the literature briefly mentioned before. This paper wants simply to carry out a semantic check on the usefulness of the resulting assessments. That is, when adopting values of the EI indicator can we identify something in common among the countries expressing similar values? If we look at the big picture coming out from the use of this indicator over a large group of countries and a long period of time can we find some useful application? In conclusion, without getting into a formal analysis of the factors determining the quantitative assessment, this paper wants to investigate whether the information provided by this indicator can be trusted as useful for sustainability analysis.

a. The main critique to be checked: EI as white noise

According to its definition EI shows the amount of primary energy needed to generate one unit of GDP in a given country and year. The indicator is mostly used in time series to study the declining ratio of energy use per unit of GDP and the corresponding increase in energy efficiency. In fact, such a research can be carried out at different levels – at the national level or at the sector/industry level of a given country or panel (Sue Wing 2008). In the latter approach the sectoral EI making it possible to focus on the energy-efficiency of technology deployed in particular sectors.

The use of EI indicator at the level of the whole economy is more problematic and it has been criticized by Giampietro et al. (2011) using the following claim: the ratio between "energy consumption per year" and "GDP per year" is "*a number without an external referent*". To support this point they illustrate the example of the value of EI of El Salvador, a developing country, which is exactly the same as that of Finland, a highly industrialized country. In their criticism they say that this is a systemic feature that can be easily explained when considering that the metabolic pace of energy per hour (the energy invested in producing and consuming goods and services) is reflected in the level of GDP per hour (reflecting the economic activity of producing and consuming goods and services). Both variables are indicators of the aggregate pace of production and consumption of goods and services in a given economy referring to different methods of quantification (energy flows versus added value flows).

Assuming that GDP and energy consumption are correlated (Giampietro et al 2011, Ch. 3) translates into saying that an indicator such as EI - based on their ratio - should be considered a "white noise indicator" rather than a measure of economic efficiency. As previously mentioned it is well known that a straight cross-country comparison shows that energy consumption and GDP are highly correlated. The long run correlation between GDP and energy in the US was highlighted by Cleveland et al. (1984), Hall et al. (1986), while Kaufmann (1992, p. 55) biophysical model for France, Germany, Japan and the United Kingdom, found that the "*link between economic activity and energy use is stronger than believed*", and "*attempts to reduce the environmental impacts of energy production and consumption will be more expensive than is commonly assumed*", pointing to the role played by energy quality for ensuring GDP growth[1].

But when carrying out a study over a large sample of countries (e.g. 133 countries of the world) and when considering a large time window (e.g. 1960-2010) can we generalize this conclusion? With this paper, I want to explore this idea and answer these questions.

2. Results of the empirical analysis

The EI indicator for 133 countries over the 1960-2010 time frame has been calculated using data on primary energy use from the International Energy Agency (2012) and real purchasing power parity international US$ GDP and population gathered by Gapminder (2011 a, b) from various sources. In this study I use two different approaches to check the validity of the results of the EI indicators to study changes in socio-economic characteristics of countries: (i) an analysis of the ability of detecting differences from countries at a given point in time (synchronic analysis); (ii) an

[1] Concerning the analysis of the role of energy quality for growth see also Stern and Kander (2010).

analysis of detecting differences of behavior of countries in time (diachronic analysis). The two approaches are described in the following sub-sections.

2.1 The synchronic analysis of the sample of 133 countries in 2009

The resulting 2009 EI indicator, presented in *Table 1* is expressed in MJ per international 2005 real dollar (MJ/US$2005ppp)[2]. Very poor countries (GDP < 2000$) do have an important fraction of their economic activity outside market transaction (subsistence). Thus, the consumption of energy for producing and consuming goods and services does not translate into the generation of a relative amount of GDP – a large fraction of these goods and services are not market-traded. For this reason, the energy intensity of some of these countries tend to be much higher than the rest[3].

While OECD countries have high values of both energy and income, many Asian, African and Latin American countries lay behind in the development stage. Countries having a high EI are mostly countries with low income suggesting that it is the denominator - i.e. GDP - making the difference in EI, because of the large fraction of economic activity associated with the production and consumption of goods and services taking place outside the market. Moreover, in developing economies a large fraction of the energy used is non commercial energy, which is greatly underestimated in energy statistics while at the same time, the vast majority of activities which in developed countries would belong to the service sector is carried out outside the market. For this reason these countries do not express the same relation between energy consumption and GDP found in developed countries.

For all these reasons, if we want to focus on the possible effect of technological development on the dematerialization of the economy (the decoupling of economic growth from consumption of energy and other resources) it is important to focus on a sample of countries expressing similar characteristics in their socio-economic structure. As soon as we enter in the group of country with a fair level of market transactions in the economy – e.g. when the GDP increases over the threshold of 5,000$ p.c. in 2009 (*Table 2* and *Figure 1*) - we find that the growing correlation between "energy" and "GDP" tends to unify the value of EI across countries, even if they are operating at different levels of economic growth. Then, within this large sample, if we focus on local clusters of countries, those defined by very similar values of EI, we can notice that within each one of these clusters we find very diverse economies.

Within the 88 countries having a GDP higher than 5,000$ p.c. in 2009 the empirical correlation between GDP and Energy use is higher than 0.6 in 52 countries (60%). To work on a

[2] For our purpose of (wide) comparison, we use 2009 as reference year, even though for some countries 2010 data are available.

[3] The 21 countries with GDP p.c. < 2000$ have an EI between 7.6 and 71.9 (with the exception of Bangladesh).

more robust sample, after selecting countries with GDP > 5,000$p.c. the 1st and 5th percentile were eliminated and the remaining 52 countries were divided into three groups of low, middle and high EI values[4]. In this way, we can better appreciate the heterogeneity of the countries belonging to a sample of economies having a homogeneous structure in terms of the mix of economic activities.

At this point, in order to have an idea of the level of energy-GDP correlation within each group, the values of both "energy use per capita" and "GDP per capita" have been visualized in a graph having these two variables on the two axes. By doing this exercise one can finally discover that the countries included in the same cluster of EI values are basically lying on a straight regression line: the diagonal of the plane defined by the two variables "energy per capita" and "GDP per capita"[5]. The distance of the values of both "energy per capita" and "GDP per capita" found in each group clearly illustrates an extreme heterogeneity of the economies considered in the analysis when considered a dimension at the time (how distant are the countries when considering GDP p.c. or when considering energy consumption p.c.), however, their position on the same regression line implies that they do have similar values of energy intensity. Coming to the detailed analysis of these three groups:

(i) the low-EI countries group is presented in *Figure 2*. It spans from Angola to Luxembourg, including Latin American and Caribbean countries, together with Germany, Japan and the Netherlands, all in the narrow range of EI = 4.45/5.69 MJ/$[6]. This range of EI values obviously hides the substantial differences between countries belonging to completely different typologies: agrarian, developed industrial and service economies.

(ii) the middle-EI countries group is presented in *Figure 3*. It includes Egypt and El Salvador, Belgium and Sweden, together with some Eastern Europe countries, Mexico and Argentina, all within a range of EI between 6.14/6.97 MJ/$. Also in this case, we find extremely diverse typologies of economies sharing a similar value of EI.

(iii) the high-EI countries group is presented in *Figure 4*. It includes higher income countries, like Finland, Australia and the USA together with Algeria, Bosnia and Bulgaria, Qatar and Brunei, all included in the narrow range of EI = 7.04/9.06MJ/$s. In this cluster, we must remark that the differences in both GDP p.c. and energy consumption per capita are very large: the GDP varies of a factor of almost 11 and the energy by a factor of 13.

2.1 The diachronic analysis of the sample of 133 countries between 1960- 2010

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[4] To note, the 1st quintile included some of the main EU countries characterized by low-EI, e.g. Denmark, Greece, Ireland, Italy, Spain, Switzerland and United Kingdom. On the contrary, the 5th quintile included most energy-rich states, but also Belarus.

[5] The regression line R^2 is > 0.97 for the three groups.

[6] The size of the bubble in the Figures 1, 2 and 3 indicates real GDP in 2009.

This unconventional analysis of the semantic of the value of EI can be extended to a diachronic analysis of the behavior of the sample of 133 over the period of time 1960-2010. Also in this case I use a representation based on a graph with the same two axes used in Fig. 2, Fig.3 and Fig. 4, but this time a video is used to show the behavior of the sample of countries in time. The video can be seen at:

https://docs.google.com/spreadsheet/ccc?key=0AorC_LlmlCWWdHJQSUpqTXZ1ZDEtTWV2TUNJWEVReVE .

It is quite obvious that there is no common trend determined by technological progress to be found in the movements of the countries included in the sample. Starting approximately in year 2000, the video shows two phenomena: 1) major Asian countries (e.g. China and India), increase their energy use per capita (as well as EI), corresponding with export rise ; 2) OECD countries reduce their energy use per capita (and EI), when starting to import energy intensive products from the former. For obvious reasons the most erratic countries are those of the Middle East, where little population benefits from giant fossil energy exports.

3. Discussion

When considering the synchronic analysis of the 88 countries with GDPp.c. > 5000, the characterization given by the EI indicator shows that the majority (58) of world's countries are included in a range between 4 and 9 MJ/US$, while western Europe countries EI lies between 4 and 6 MJ/US$, an exception is Belgium (7MJ/US$), while Iceland is a clear outlier (11MJ/US$) because of its extraordinary geothermal sources. However, if rather than adopting an indicator based on a single number (the EI index), we try to characterize the economies using explicitly the two variables determining the EI indicator, providing two separate assessments based on energy use per capita *and* GDP per capita (e.g. on a plane), the resulting analysis becomes much more useful to characterize the biophysical performance of the economy.

In this richer analysis based on two variables, if we want to study the factors that generate the differences found over the two axes of both: (i) energy use p.c. (y-axis); and (ii) GDP p.c. (x-axis) the next "natural" analytical step is to open the black-box of the society and move to a sector-level description. In this way, it becomes possible to study how the energy intensity of the economy can be explained by looking at: (i) the values of the "economic intensity" of the various economic sectors which is quite different for different sectors. Primary and Secondary sectors are much more energy intense than the Service and Government sector; and (ii) the relative size of these sectors determining their relative weight of sector-specific characteristics in the overall generation of GDP. In relation to this point we can flag to the reader that the MuSIASEM approach has been developed exactly to provide this type of insight about the different characteristics of structural and functional compartments of an economy determining the values of overall changes in the characteristics of the economy (Giampietro et al. 2009).

When considering the diachronic analysis of the 133 countries in the period 1960-2010 no generalized trend toward reduced values of EI can be detected. Commenting, one can say that beside the problem generated by neglecting the issue of scale (when assessing the characteristics of the economy at the level of the whole country there are too many factors affecting the value of EI) there are at least three reasons (the first has already been briefly described before) explaining why Energy Intensity is not useful to carry out comparisons across countries at different level of economic development:

(1) both factors of the ratio making up EI have problems when used to characterize and compare typologies of very different economic systems. In relation to the assessment of the energy throughput p.c./year, the aggregation of different forms of energy can become problematic when the quality of the various energy forms considered is quite different – e.g. electricity, coal, biomass (Giampietro et al. 2011; 2012). In relation to the assessment of GDP p.c./year, the assumptions about the (measurable) economic transactions forming GDP can imply: the missing of an important part of the economy both in very poor countries where the majority of the population is engaged in activities taking place outside market transactions and the missing of important aspects of the performance of the economy in developed countries (van den Bergh, 2010);

(2) the EI ratio ignores differences in demographic characteristics (e.g. differences in dependency ratio determining the requirement of activities in the service sector) and the effects of externalization to other countries associated with the terms of trade, making it possible structural changes of the economy. In fact, the light-industry/service economy toward which post-industrial OECD countries converge is only possible because the activity of secondary (and a big part of primary) sector has been externalized to emerging economies – e.g. the BRICS. In this case, "there" (in the emerging economies) is the energy (and pollution) of the goods consumed "here" (in developed ones). As stated straightforwardly by Schaltegger and Csutora (p. 2): "*Much of the apparent reductions of carbon emissions* [in the European Union] *are due to the fact that they were 'exported' with major shifts of industrial production to Asia*". The phenomenon of energy/pollution externalization can be seen clearly in the video showing the time series on two axes (described in Section 2.1);

(3) the excessive reliance of modern economies on credit leverage and debt muddles the possibility of detecting whether or not the goods and services consumed by developed countries (and not produced) have been paid by trading an equivalent value of goods and services produced in the

importing countries or rather by making additional debt. So countries more effective in paying their import by making debt will be seen as more effective in "dematerializing" their economies.

4. Conclusions

The answer to the title question is negative. As stated by Smil: "*the EI ratio must be approached with great caution. If the measure is interpreted in a naive, ahistorical, and abstract fashion […] its use only reinforces some inaccurate notions, and it misleads more than it enlightens. Deconstruction of the measure offers a deeper understanding of underlying realities, uncovers a number of serious data limitations, leads to a careful interpretation of differences in levels and trends, and helps to avoid simplistic, and hence potentially counterproductive, conclusions*." (Smil, 2003, pp. 70-71).

Since the energy throughput of an economy and its corresponding GDP in developed economies are highly correlated, their ratio cannot give useful information about the state of economic development in relation to the decoupling or dematerialization of modern economies. In this unconventional empirical analysis I decided to go for a semantic quality check, rather than for another "rigorous" formal test of this fact. In fact, it seems that rigorous formal tests, so far, were not able to detect the semantic weakness of the Energy Intensity indicator those that use it. Maybe an approach based on simple common sense may result more effective.

Probably, the success of the EI indicator may be explained by the fact that it can be used to support "rosy hypotheses" about the sustainability of modern economies – e.g. economic dematerialization of developed economies and Environmental Kuznets Curve (EKC) (Vehmas et al. 2007). Put it in another way, the EI indicator is used to provide empirical evidence of the decrease in the consumption of energy per unit of economic activity, which is explained by increases in efficiency – the effect of "the invisible hand" of the market and human ingenuity teaming together - ultimately resulting in better environmental performance: lower emissions per unit of GDP. However, a more detailed analysis of the same trends, carried out across multiple scales provides a different picture. The societal transition toward the service economy experienced by advanced economies, is determined by an externalization of energy and pollution to the countries producing the (now) imported goods (Giampietro et al. 2011) and, therefore, the approach of EI is far from satisfactory as an indicator of performance in relation to sustainability issues (Recalde and Ramos-Martin 2012).

To overcome the limits of the EI approach it is important to develop more complex descriptions of the functioning of modern economies avoiding the dangerous compression of non-equivalent information into aggregate indices referring to a single scale of analysis. An integrated assessment of sustainability requires the handling of different kind of information based on: 1) economic and biophysical dimensions; and 2) a multi-scale description capable to characterize in quantitative terms production and consumption across different compartments of the society.

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