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Are modern economies following a sustainable energy consumption path?

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ABSTRACT

In the frame of an enhanced environmental discussion regarding the existence and convenience of energy decoupling or dematerialization, this paper studies the past trends of global primary energy resources in relation to monetary and demographic variables in a top-down framework. This paper aims at contributing to the literature on dematerialization and energy sustainability from a dynamic perspective, with the purpose of shedding light on some questions, such as the real existence of an intergenerational energy dematerialization. To this purpose we use the phase diagrams of energy intensity and the product generational dematerialization (PGD) indicator for the period 1970–2011 for the global economy, the OECD and Latin American and Caribbean regions, China and India. While from energy intensity perspective a decoupling trend can be observed, we found no evidence for global intergenerational sustainable energy path in the long term. In this context, some questions related to the real impact of past and future environmental policies on energy consumption arise, especially in relation to developing countries.

Introduction

During the last decades there has been a clear and growing scientific consensus that Global Warming is highly related to human activities, which are the key driver of the Greenhouse Gas (GHG) emissions (Anderegg, 2010; Doran and Zimmerman, 2009; Hansen et al., 2008; IPCC, 2013; Oreskes, 2004), something that was reinforced by the Fifth Assessment Report released in September 2013 (IPCC, 2013). As stated by Rockström et al. (2009) since industrial revolution, the humanity is going through an *Anthropocene* era characterized by rising atmospheric carbon dioxide (CO_2) concentrations. While the pre-industrial value of CO_2 was around 280 p.p.m., according to information from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory,[1] in June 2013 the atmospheric CO_2 concentration was nearly 400 p.p.m, which is far from the initial objective of reduction to 350 p.p.m. and within the so called "*critical threshold between 350 and 550 p.p.m*" (Hansen et al., 2008).

Most anthropogenic GHG emissions are energy-related CO_2, emissions resulting from the combustion of fossil derivatives (DOI/IEA, 2013). In this sense, the key determinants for energy demand will be crucial for the evolution of GHG emission trends. As argued in the global energy assessment from the IIASA "*The energy system is driven by the demand for energy services — a demand that in turn is driven by population and demographic trends, by the level of economic activity and income, and by technological and structural changes*" (Yeager et al., 2012). Hence, *population, economic activity, and technology performance* will be crucial to understand the projections of *energy demand and emission trends*.

According to the different scenarios developed by both the IPCC (2001) and Riahi et al. (2012), population will continue to grow, from 6.8 billion to 9–15 billons in 2100 with increasing urbanization rates. Fiksel (2012) states that, as global population approaches to 9 billion people (mainly concentrated in urban areas) continued environmental pollution and global warming can be expected. Most of this population growth will happen in the developing world, with the consequent impact on energy emissions. According to the information from the International Energy Outlook, energy-related emission grew significantly in developing non-OECD countries in the period 2001–2012 (nearly 80%) and remained nearly stable in the OECD region (DOI/IEA, 2013) and these projections are supposed to be maintained. Different policy scenarios stress as those in 2040 and 2050 that developing countries will be the most energy consumer and emitting countries, because their economies and population will grow at a higher rate than developed ones, and they will probably "*rely on fossil fuels to meet this fast-paced growth in energy demand*" (DOI/IEA, 2013; IPCC, 2013).

These *stylized facts* have reinforced the interest for the dematerialization or decoupling hypothesis in the economic literature. Even though the discussion on the reduction of energy and material consumption along the development process initiated a long time ago (see for instance: Larson et al., 1986; Williams and Larson, 1986 among others),

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[1] http://www.esrl.noaa.gov/.

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to some extent the attention on this topic boosted after a special number of the Ecological Economics Journal in 1998.[2] According to this idea, the relative use of energy and material reduce along the economic growth path, as a result and interaction of different effects, and therefore economic growth could represent a solution to ecological problems. Certainly, for some authors and policymakers, dematerialization may contribute to ease conflicts between the economy and the environment (Wieringa et al., 1992). The United Nation Environment Programme (UNEP) (2011) argues that "*decoupling is one of the most important challenges for the near future, as technological and systematic innovation in combination with rapid urbanization offers a historic opportunity to turn decoupling from theory into reality*". Contrarily, other authors argue that the optimism on the dematerialization process, as well as predictions on future decoupling, is overvalued since developed countries seem to be in a re-materialization phase, and their previous dematerialization process may have been due to a reallocation of pollutant and energy (material) intensive industries (Ramos-Martin, 2005).

In this context, there are different questions arising from recent data and empirical studies. Is the negative trend of energy consumption per GDP a good indicator for reduced environmental pressure? Is the recent trend of worldwide energy intensity sustainable? Does it mean that the world is pursuing a long term energy dematerialization?

In this paper we study the past trends of energy consumption per unit of GDP and the evolution of the relation between the rate of growth of energy consumption and population for different samples of countries, to conclude whether there exists (or not) a trend to a sustainable energy consumption path and an intergenerational energy dematerialization. The objective is to contribute to the literature on dematerialization from a dynamic perspective, in a top-down approach,[3] throughout the use of both phase diagrams and intergenerational dematerialization ratio in different regions. Even though the indicator proposed for the study of the demographic dematerialization has not been widely used in the recent literature, its major strength is the capability to complement the existing studies, which are mainly concentrated on monetary intensive variables. The incorporation of the demographic dimension, allows the addressing of a second component of the man-made environmental pressure. We consider that the study of the potential sustainable energy path of the economies and the reduction of environmental impacts require the comprehension of the multidimensionality of the problem.

The article is structured in four sections as follows: the Literature review section provides a brief overview of the literature and the main criticism around the energy dematerialization studies. The Empirical analysis section presents the data and methodology proposed. The Results section presents the results of the empirical analysis using the energy intensity paths and the GHG emission evolution, phase diagrams and the energy intergenerational dematerialization. Finally, we present a discussion and conclusion.

Literature review

As mentioned above, the idea of the reduction of the energy and material use as a result of the economic growth has been discussed by several decades. Though, there is no unique definition for this concept. Different authors, for instance Cleveland and Ruth (1999), agree on defining dematerialization or decoupling as the delinking of income and the use of nature; this is the possibility of a reduction in the use of energy and/or materials either in absolute or relative terms. One of the most common applications of the dematerialization concept is the approach of the intensity of use firstly stated by Malenbaum (1978), according to which income is the main factor explaining material and energy consumption (Ramos-Martin, 2005). This hypothesis supports the theory of the environmental Kuznets curve (EKC),[4] which states the existence of an inverted-U shaped relationship between economic growth and environmental degradation. In the frame of this hypothesis, environmental degradation increases with economic activity up to a *turning point*, after this point the augments in income are associated to increases in environmental quality (Grossman and Krueger, 1991; Panayotou, 1993; Selden and Song, 1994; Shafik and Bandopadhyay, 1992). Contrarily to this argument, Jevons (1990) suggested that *rebound effects* are very important, and that productivity improvements and economic growth are energy driven. Therefore, technological progress could have the contrary effect and increase energy demand instead of reducing it (Recalde and Ramos-Martin, 2012). According to different authors, instead of implying reductions in energy consumption and improvements in environmental conditions energy efficiency may result in augmented demand and use of energy (Berkhout et al., 2000; Birol and Keppler, 2000; Haas and Biermayr, 2000; Jaccard and Bataille, 2000; Laitner, 2000; Milne and Boardman, 2000; Polimeni and Polimeni, 2006; Roy, 2000). Then, energy efficiency, conservation and technological improvement, may worsen the energy prospects for developed nations (Alcott and Greenstone, 2012). Nonetheless, the key point for these arguments is the ceteris paribus condition. *If nothing else changes*, the improvements in energy efficiency will decrease the relative cost of energy, increase the disposable income and may result in increased energy demand (either the original energy service, a new energy service, or some other use of energy) (Jaccard et al., 2012; Yeager et al., 2012). However, the situation could be different if there are changes in energy prices or if, as argued by Larson et al. (1986) and Williams and Larson (1986), consumer preferences change with rising income (or as a result of other cultural reasons) in favor of less energy and material intensive products.

The empirical study of dematerialization has been performed by different authors with different methodologies. Many of these studies have been developed in the frame of the previously mentioned EKC (Agras and Chapman, 1999; Luzzati and Orsini, 2009; Richmond and Kaufmann, 2006; Stern and Cleveland, 2004; Suri and Chapman, 1998; Zilio and Recalde, 2011, among others), through the study of the evolution of the energy intensity (Goldemberg and Siqueira Prado, 2011; Rühl et al., 2012; UNEP, 2011), by econometric studies on different absolute variables (Bernardini and Galli, 1993; Sun, 2003; Sun and Meristo, 1999) and by more novelty methodologies such as the decomposition analysis, which includes the structural decomposition analysis (SDA) and index decomposition analysis (IDA) (Ang, 2004; Ang and Zhang, 2000; Hoekstra and van der Bergh, 2003; Su and Ang, 2012, among others).

The majority of the energy dematerialization studies are performed from an energy monetary perspective, using an intensive indicator: the energy intensity (EI), which is the energy needed to produce a unit of output usually defined as the ratio between the final (or primary) energy consumed and the GDP, intending to reflect how efficiently an economy uses energy to generate added value (Kaufmann, 1992). Most of the results of these studies show a decreasing trend in the historical evolution of energy intensity in many developed countries, which may be supporting the existence of a decoupling process (Gales et al., 2007; Rühl et al., 2012, among others). Nonetheless, there are different arguments against this idea. This phenomena should be mainly

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[2] See: Ecological Economics 25 (2) pp 143–232.

[3] The differences between "top-down" and "bottom-up" models are addressed by the Third Assessment Report of the Working Group III of the IPCC (2001). While the former use aggregate economic variables, the latter considers specific technological options for mitigation policies. According to that report the top-down models have been more widely used because of their simplicity and the existence of aggregate information. However, those models face many criticisms, particularly when used for analyzing the potential for energy decoupling. As stated by different specialists the aggregate models do not capture the sectorial complexity of the demand and supply of energy and the characteristics of different technologies. We do recognize the relevance of this aspect, but this is a very initial approach to the theme and future extensions will be performed with more disaggregated information.

[4] For a complete review on the theoretical and empirical literature of the EKC see: Zilio (2011).

attributed to other strategies rather than energy and environmental policies, such as the *within* substitution of fuels, or the reallocation of energy intensive industries from developed to developing countries which is known as the Haven Pollution Hypothesis (HPH) (Cole, 2004; Cole and Elliot, 2005; Jenkins, 2003; Wagner, 2008). According to the HPH the decoupling of energy in developed nations has been partly due to the reallocation of the industries (Recalde and Ramos-Martin, 2012).

Furthermore, the sole use of energy intensity to assess dematerialization or environmental impact has been highly criticized because, as stated by Ramos-Martin (2005), a reduction in consumption per unit of output does not necessarily imply a reduction in anthropogenic environmental impact as the trend of the environmental impact is determined by the different rates at which the consumption per unit of output is reduced compared to the growth of production of output per capita. The key point in this respect is whether the historical evolution of an aggregate relative indicator, such as the intensity of use of energy, is good enough to represent the historical evolution of an absolute indicator for the environmental pressure or not. In fact, Giampietro et al. (2012) argue about the possibility of assessing the sustainability of a system based only on intensive variables. Additionally, Fiorito (2010) states that one of the problems of the energy intensity indicator is that "*it compress into a number different pieces of information referring to different dimensions (monetary and energy flows) and to different scales*". However, there are different interesting alternative approaches to study the energy consumption, environmental impact and potential existence of decoupling processes integrating material, monetary and demographic variables; a widely used example of these methodologies is the Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Eisenmenger et al., 2007; Falconí-Benítez, 2001; Giampietro and Mayumi, 1997, 2000; Giampietro et al., 2009; Ramos-Martin, 2001; Ramos-Martin et al., 2007; Recalde and Ramos-Martin, 2012).

Empirical analysis

Methodology

In order to study the existence of decoupling processes with a broad vision of the problem, we develop a dynamic study integrated by two methodologies: the phase diagrams and the product generational dematerialization.

In the first place, as stated by Ramos-Martin (2005) the use of linear techniques is not the most adequate technique to describe the behavior of temporal and intermittent changes in socio economic systems, which are mainly characterized by the discontinuity of equilibrium. Then, the phase diagram may be a very useful and used methodology to study energy intensity phases (De Bruyn, 1999; Ramos-Martin, 2005; Recalde and Ramos-Martin, 2012; Unruh and Moomaw, 1998).

The phase diagram consists on the representation of the energy intensity in the year t in the Y-axis, and the energy intensity in t − 1 in X-axis and the points obtained are joined. If the country has displayed an increased path in energy intensity, then the diagram will show a relative straight positive line, implying greater intensities over the years. Contrarily, if the country has faced reductions in energy intensity there would be a negative right-hand to left-hand line. In those cases in which a country faces a situation of punctuated equilibrium, then the diagram shows different attractor points, in which energy intensity moves around a certain value: the attractor points. Although the desired trend would be a reduction in energy intensities, it has been tested that developed economies presented attractor points in their energy intensity, showing that development process is characterized by step-wise (De Bruyn, 1999 in Ramos-Martin, 2005).

In the second place, as argued by the Global Assessment Report from IIASA, population and demographic trends are also key drivers for energy demand, and therefore for GHG emissions. In this sense, Ziolkowska y Ziolkowski (2011) insist that the majority of dematerialization methodologies do not inform about the reduction of materials (or energy) compared to population as most of the literature on decoupling relates only to economic variables.

The role of population in decoupling enhances with the recognition of the intergenerational, and many times irreversible, characteristic of environmental changes. The dematerialization/materialization processes may be different considering the dynamics of population growth of different regions, which is particularly important for developing countries.[5]

Hence, following Ziolkowska y Ziolkowski (2011) in this paper we use the *product generational dematerialization* (PGD) indicator to discuss the dematerialization from a global and dynamic perspective. This indicator is a useful measure to complement energy sustainability analysis, as it shows the pace and direction of changes in energy consumption and population. As stated by the authors, if the rate of growth of energy consumption exceeds the rate of growth of population, then the economy is following a non-sustainable intergenerational path, or an energy materialization trend; otherwise, it will be in an intergenerational sustainable consumption path (or energy decoupling). The key contribution of this indicator to this paper is the intergenerational analysis of the sustainable energy paths to complement the existence or not of an energy decoupling trend of the economies.

There are different reasons to choose the PGD to complement the study of dematerialization instead of other indicators. The first and probably the most important reason is that it allows the capturing of the dynamic effect of consumption and population growth, thus it can be a good indicator of a long term intergenerational behavior. To some extent, as argued by Ziolkowska and Ziolkowski (2011), the PGD can be interpreted as an equivalent of changes in the energy consumption per capita, expressed in relative values. It is also easy to calculate an indicator that does not demand a lot of information, which constitutes an advantage particularly in developing counties where statistical information may be difficult to find. Finally, one of the benefits of using the PGD instead of the energy consumption per capita indicator is that the former provides not only the relative direction of the change (positive or negative) but also the scale of the change; it allows the comparing of real variations in energy consumption and population.

Then, the PGD is the difference between population and energy consumption dynamics in different time periods. Formally it is defined as:

$$\mathrm{PGD} = \left(\frac{\mathrm{P_t}}{\mathrm{P_{t-1}}}\right) * 100 - \left(\frac{\mathrm{E_t}}{\mathrm{E_{t-1}}}\right) * 100$$

where:

PGD	product generational dematerialization
P_t	population in time t
$P_{t\,=\,1}$	population in time t − 1
E_t	energy use (consumption) in time t
$E_{t\,-\,1}$	energy use (consumption) in time t − 1

The interpretation of the indicator provided by Ziolkowska and Ziolkowski (2011) is straightforward: a positive value denotes that less energy (in comparison to the base-case) is used in the economy by unchanged population; or that the population is growing faster than the energy consumption. Then, this situation shows a sustainable policy in which energy resources can be saved. Otherwise, a negative value of the PGD denotes either higher consumption of energy by unchanged population or energy consumption growing faster than population.

Finally, in order to compare our results to the original paper of Ziolkowska and Ziolkowski (2011), we use Total Primary Energy Supply instead of oil crude consumption. This measure includes the

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[5] In the case of the two samples under study, population growth differs between 1.1 and 0.6% between 2000 and 2010 for LA&C and OECD countries respectively (World Bank, 2012).

consumption of total primary energy sources (coal, oil, gas, nuclear, hydro, renewables, etc.). The main reason to propose this change is that we consider the latter as a better proxy for global environmental pressure than oil. As it has been largely argued in the economic literature, inter fuel substitutions played a crucial role in the reduction of energy intensity and environmental pressure around the world (Cleveland, 2003; Cleveland et al., 1998; Hall et al., 1986; Stern, 2004). Then it could be the case that a country has changed it energy matrix, substituting oil by any other fuel and therefore the relation energy (oil) consumption/population decrease, even though global energy consumption/population increased.

Data

We use data for the period 1960–2009 for two different groups of countries: the Organisation for Economic Co-operation and Development Countries (OECD) and the LA&C[6] countries. The former is composed by a group of 31 high income OECD countries that according to the World Bank Database are those in which 2010 GNI per capita was 12,276 US dollars or more. The latter, is composed of all 41 countries of the Latin American & Caribbean Region. The complete list of countries is available in Tables A1 and A2 of the annex. In order to complement the study we include two countries, chosen because of their economic relevance and their large, fast-growing economies and significant influence on regional and global affairs and which belong to the association of leading emerging economies (BRICS): China and India. In order to avoid data problems arising from the use of different sources of information, for all the samples we use information from the World Bank Database.[7]

As a proxy for Primary Energy Consumption we use Primary Energy Use, measured in kilotons of oil equivalent (ktoe), which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. For GHG we used carbon dioxide emissions (CO_2) arising from the burning of fossil fuels and the manufacture of cement. Energy Intensity is defined as energy use per unit of output, measured in toe per U $S1,000,000 (constant 2005 US dollars), based on the GDP at purchaser's prices as estimated by the Work Bank. According to the information from that database, for the case of GDP the data is converted from domestic currencies using official exchange rates and for the countries where the official exchange rate does not reflect the rate effectively applied to actual foreign exchange transactions an alternative conversion factor is used.[8] Finally, total population as informed by the World Bank database is based on de facto definition of population, which counts all residents regardless of legal status or citizenship except for refugees not permanently settled in the country of asylum, who are generally considered part of the population of their country of origin; the values shown are midyear estimates. Table 1 shows the statistical summary of the variables for each one of the countries or regions analyzed.

Results

Energy consumption and economic growth: a preliminary view

Figs. 1 and 2 show the evolution of energy use and CO_2 emissions in the regions of LA&C and OECD. In both cases there is a clear positive trend along the period, with a reduction (more relevant in the OECD case) during the 2007–2009 years. As stated by Sheinbaum et al. (2011), the increase in the energy-related CO_2 during the years 1990–2006 in the Latin American region is mainly due to the growth of the activity level and changes in the composition of GDP. Despite sharing the same trend it is important to note that these regions have a very different impact on Global Warming. LA&C has a marginal role as an emitter region; it is responsible only for 5.1% of worldwide CO_2 emissions from burning fossil fuels and cement manufacture. This different impact may be related to the composition of the energy matrix. In 2010, 81.1% out of Total Primary Energy (TPE) in OECD came from hydrocarbons with coal and peat accounting for nearly 27.3% and renewable sources (hydro, geothermal, solar, wind, biofuels and waste) representing 13.2%. Contrarily, in the same year, 69% of TPE in LA&C region were represented by hydrocarbons (only 3% coal and peat) and 30% renewable sources (primarily hydro and biomass).

Energy use behaves differently in both regions. It displays a positive annual rate of growth for every period in LA&C but in OECD it reduced in two sub-periods. Firstly, after the first oil shock when oil prices increased more than 350% between 1973 and 1974 (following ever since a high positive trend), energy use fell 1.30 and 2.25% in 1974 and 1975 respectively. The impact of the 1979 energy crisis over energy consumption was even more pronounced, although the increase in the average price of crude oil was 262% between 1978 and 1980.[9] As a result developed economies, mostly net energy importers, reduced their energy consumption. In the case of OECD region, this reduction accounted for 7.84% between 1978 and 1982. Geller et al. (2006) argue that since 1973 industrialized nations became more efficient as a result of energy efficiency policies in the wake of the 1970 oil crises.

China and India also display a growing trend for both energy use and CO_2 emissions (Figs. 3 and 4). The case of China is particularly interesting because this country is currently the leader emitting country of CO_2. In 2011, it accounted for 25.5% of total world emissions according to the Key World Statistics 2013 from the OECD/IEA (2013); although its per capita emissions are significantly lower than those from developed regions. Both energy use and CO_2 emissions increased at the beginning of the millennium; moreover, the annual rate of growth of energy use increased from 5.64% in 2002 to 13.85% in 2003 and from 5.92% to 22.42% for emissions, and reduced in the 2010/2011 (maybe as a reaction to the international financial crisis). In this case also the evolution can be linked to the composition of the energy matrix: in 2010 87% of TPE came from hydrocarbons (67% coal and peat), with the share of coal and peat increasing significantly since 2002 (OECD/IEA, 2013).

The pattern of the phase diagram of the energy intensities of the OECD and LA&C regions is very different. That of the former displays the desired left decreasing trend from the beginning of the sixties, with only one attractor points at the beginning of the series (between 1960 and 1979), showing continuity in the historical reduction in energy intensity. Contrarily, the latter region is characterized by at least five attractor points: 1975–1980 (249–253 tep/U$S); 1982–1991 (around 300–305 tep/U$S); 1992–1999 (290–295 tep/U$S); 2000–2004 (285–290 tep/U$S), and a 2007–2011 (238–243 tep/U$S).

The driving forces of the decreasing trend of the energy intensity of OECD countries have been highly studied and discussed. On the one hand there is the idea that energy policies and increases in energy efficiency have reduced energy consumption by GDP (Geller et al., 2006). On the other hand, some authors stress the impact of the delocalization of energy intensive and polluting industries from the European Union and the United States to underdeveloped and developing regions in the frame of the HPH (Gereffi, 2001; Gereffi et al., 2008).

In contrast, the erratic evolution of the energy intensity in LA&C region with a clear increase between 1979 and 1991 may be the result of the irregular evolution of GDP. Recalde and Ramos-Martin (2012) argue that the increase in energy intensity in LA&C during the eighties (the attractor point shown in the right upper corner of Fig. 4 can be partially

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[6] Due to restrictions in the data availability the analysis for the LA&C region is only defined for the 1971–2009 period.

[7] Available at: http://databank.worldbank.org/data/views/variableselection/selectvariables.aspx?source=world-development-indicators.

[8] For the estimation we used GDP at purchaser's prices instead of purchasing power parity GDP, because for all the countries and group of countries analyzed in this paper, except OECD, this data is available only for the 1980–2011 period instead of that of 1970–2011. Therefore, we prioritized the longer period of data for this study.

[9] Information on crude oil prices from BP Statistical Review of World Energy, available at: http://www.bp.com/statisticalreview.

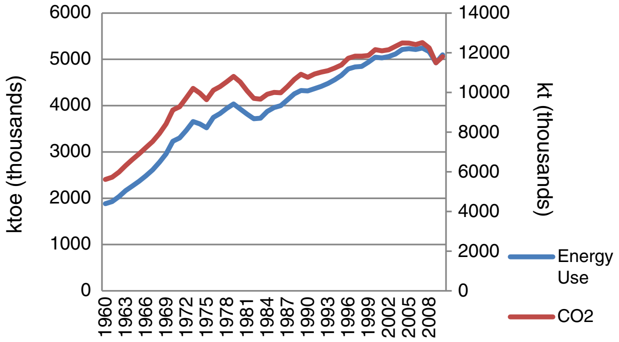
Table 1
Statistical summary of the variables.[1]

OECD						
		Obs.	Mean	St. dev.	Min	Max
PEU	Primary energy use (ktoe)	51	3,962,792	990,174	1,882,022 (1960)	5,244,659 (2007)
CO_2	Carbon dioxide emissions from fossil fuels burning and manufacture of cement (kt)	51	10,146,050	1,931,384	5,615,630 (1960)	12,512,291 (2007)
Pop	Total population	52	889,072,068	96,141,305	710,789,301 (1960)	1,046,821,925 (2011)
EI	Energy intensity (toe/Mill. 2005 US dollar)	52	200	38	136 (2011)	257 (1970)
LA&C						
PEU	Primary energy use (ktoe)	41	498,444	155,624	240,917 (1971)	809,831 (2010)
CO_2	Carbon dioxide emissions from fossil fuels burning and manufacture of cement (kt)	41	1,094,990	330,429	543,108 (1971)	1,733,152 (2010)
Pop	Total population	42	45,1098,726	94,304,512	293,930,082 (1971)	601,775,370 (2010)
EI	Energy intensity (toe/Mill. 2005 US dollar)	42	252	6	238 (2011)	263 (1983)
China						
PEU	Primary energy use (ktoe)	41	1,012,261	555,316	391,551 (1971)	2,516,731 (2010)
CO_2	Carbon dioxide emissions from fossil fuels burning and manufacture of cement (kt)	41	3,059,067	1,987,707	876,633 (1971)	8,286,891 (2010)
Pop	Total population	42	1,129,396,707	155,878,122	841,105,000 (1971)	1,344,130,000 (2011)
EI	Energy intensity (toe/Mill. 2005 US dollar)	42	1694	945	650 (2011)	3264 (1977)
India						
PEU	Primary energy use (ktoe)	41	351,111	158,513	156,464 (1971)	723,743 (2010)
CO_2	Carbon dioxide emissions from fossil fuels burning and manufacture of cement (kt)	41	821,522	517,786	205,869 (1971)	2,008,822 (2010)
Pop	Total population	42	888,473,191	201,055,869	567,805,061 (1971)	1,221,156,319 (2011)
EI	Energy intensity (toe/Mill. 2005 US dollar)	42	861	154	565 (2011)	1069 (1964)

[1] For min and max values, corresponding years are shown in brackets.

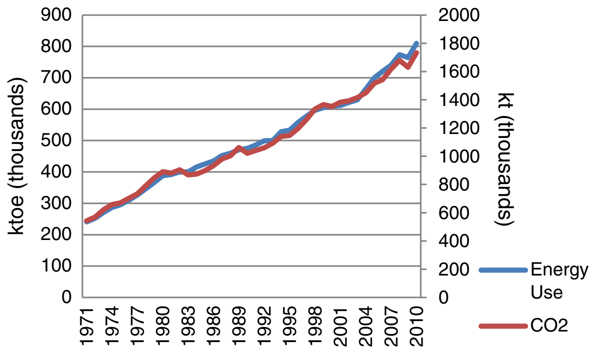
explained by the regional financial crisis at the beginning of the 1980s. The contraction of economic activity and the devaluation of local currencies in most of the countries of the region may have been the main reasons for the increase in energy intensity; while the following decrease in energy intensity may have not been the result of energy efficiency policies but rather of stronger currencies and economic recovery. The second attractor point (1992–1999) relates to the crisis of the mid-nineties in the region, which can be linked to the boundaries confronted by the neoliberal model implemented in the late eighties and early nineties. Finally, at the beginning of the millennium the economies faced a new reduction in their GDP (without a reduction in energy use) and more recently in the context of the global financial crises the last attractor point has arisen.

It is important to drive the attention to China and India, which in contrast to the case of LA&C countries, display the “desired” trend. However, in spite of this, in 2011 EI remained around 600 tep/U$$ in both cases. Reductions in energy intensity have been particularly more important in China than in India (from 3093 to 650 tep/U$$). Both



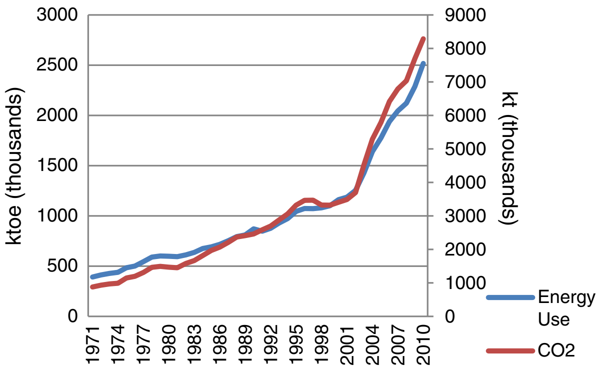
Source: Based on Climate Change and Energy & Mining World Bank Database12

Fig. 1. Evolution of energy use and CO_2 emissions in OECD, 1960–2010. Source: based on Climate Change and Energy & Mining World Bank Database. For all the variables from this and the following tables please follow the link to the database: http://databank.worldbank.org/data/views/variableselection/selectvariables.aspx?source=world-development-indicators#.



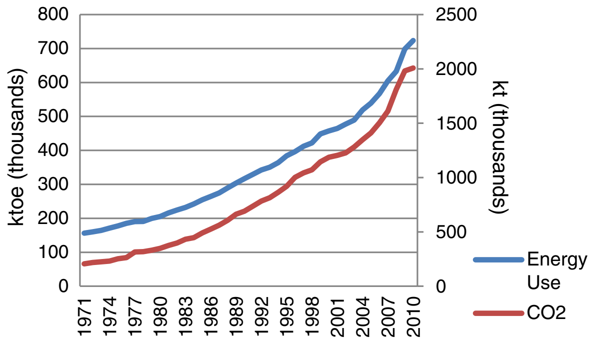
Source: Based on Climate Change and Energy & Mining World Bank Database

Fig. 2. Evolution of energy use and CO_2 emissions in LA&C, 1970–2010. Source: based on Climate Change and Energy & Mining World Bank Database.



Source: Based on Climate Change and Energy & Mining World Bank Database

Fig. 3. Evolution of energy use and CO_2 emissions in China, 1970–2010.
Source: based on Climate Change and Energy & Mining World Bank Database.

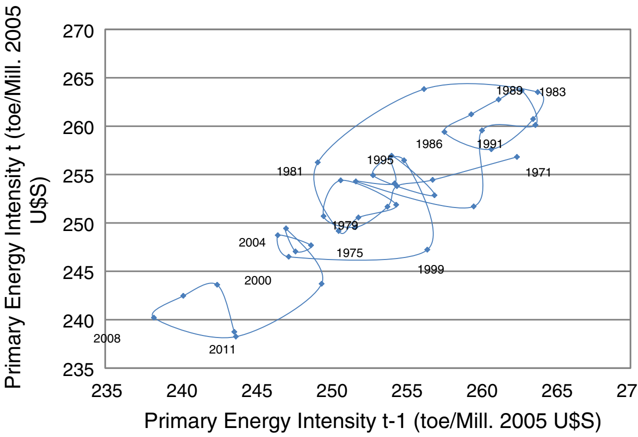


Source: Based on Climate Change and Energy & Mining World Bank Database

Fig. 4. Evolution of energy use and CO_2 emissions in India, 1970–2010.
Source: based on Climate Change and Energy & Mining World Bank Database.

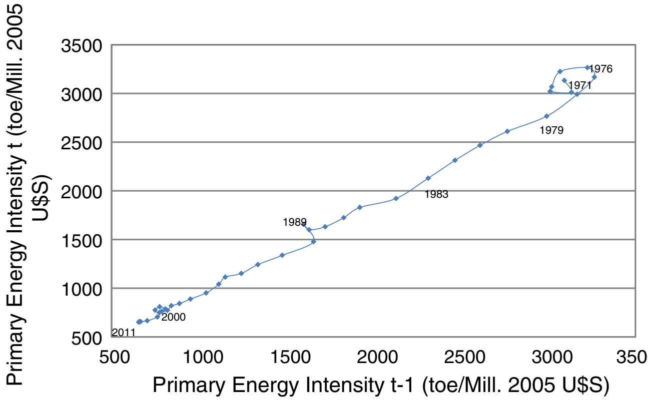
economies also display two attractor points: at the beginning of the seventies and in the late eighties; and for the Indian case, the effect of the global financial crises may have had an impact also (Figs. 5, 6, 7 and 8).

It is straightforward, that even though energy intensities may display a decreasing left trend in some cases, total energy use, as well as total CO_2 emissions, displays a positive trend. In this sense, a relative indicator showing a (monetary) de-linking process is only indicative of weak dematerialization, while the strong or absolute dematerialization would be clear if there were a decrease in the total consumption of energy in the regions. The latter would also be indicative of a reduction of total environmental pressure of the economies or a change in the energy metabolism of the system (Ramos-Martin, 2005).



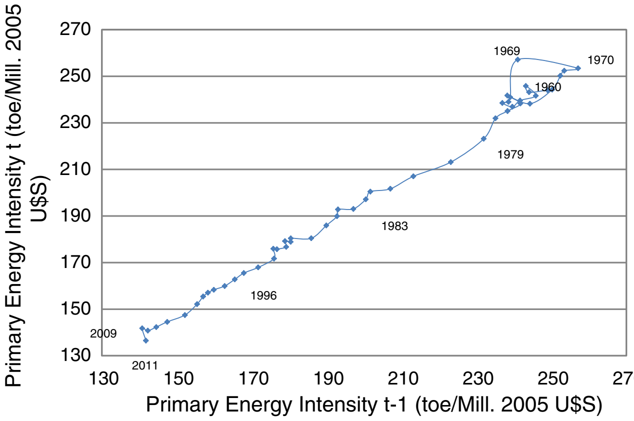
Source: Based on Energy & Mining World Bank Database

Fig. 6. Phase diagram for LA&C, 1970–2011.
Source: based on Energy & Mining World Bank Database.



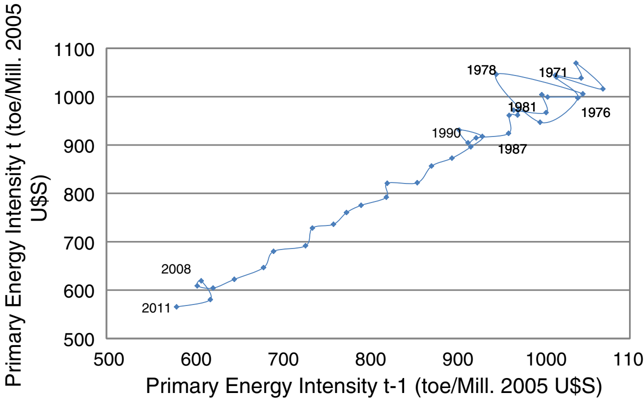
Source: Based on Energy & Mining World Bank Database

Fig. 7. Phase diagram for China, 1971–2011.
Source: based on Energy & Mining World Bank Database.



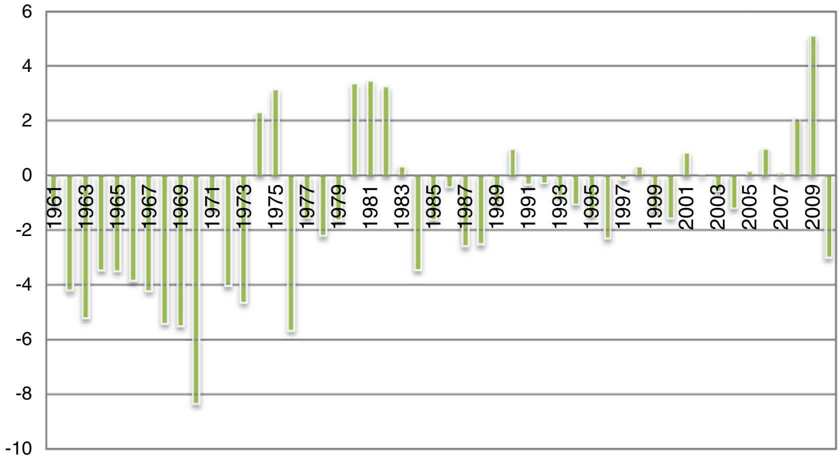
Source: Based on Energy & Mining World Bank Database

Fig. 5. Phase diagram for OECD, 1960–2011.
Source: based on Energy & Mining World Bank Database.



Source: Based on Energy & Mining World Bank Database

Fig. 8. Phase diagram for India, 1971–2011.
Source: based on Energy & Mining World Bank Database.



Source: Calculated based on Economic Policy & External Debt and Climate Change World Bank Database

Fig. 9. PGD indicator for energy use in the OECD economies in 1961–2011.
Source: calculated based on Economic Policy & External Debt and Climate Change World Bank Database.

Decoupling paths?

Figs. 9 and 10 present the results of the PGD for OECD and LA&C, denoting that none of the regions attempts to pursue a long term product generational dematerialization, except for some periods.

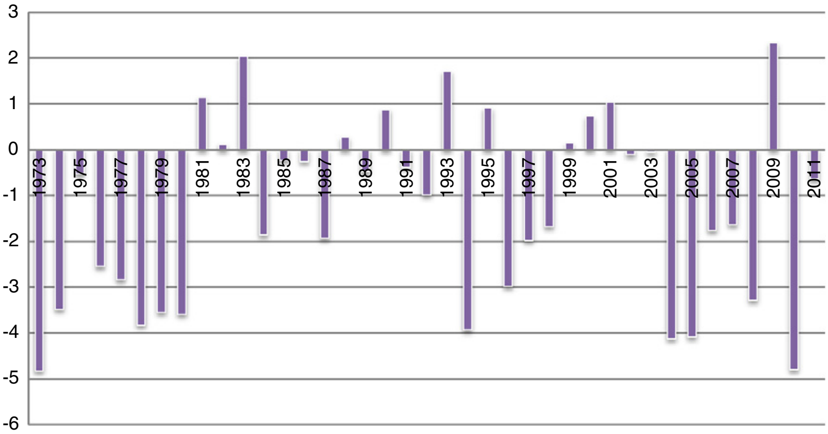
According to Fig. 9, OECD has one short-term dematerialization period: 1974–1975, and two long-term one 1979–1983, and 2005–2009. During these years the PGD was positive, indicating that the rate of growth of energy use per capita was lower than the rest of the years. The highest dematerialization was 5.20% in 2009; while the highest materialization was found in 1970 (−8.34%). Nonetheless, the results show that the total PGD for the period 1960–2010 was −61.40%.

Fig. 10 shows the results of PGD for LA&C region. This developing region does not seem to be pursuing a sustainable energy consumption path, as energy use has grown at a higher rate than population. The intergenerational energy materialization of this region is even more pronounced during the seventies and from mid-twenties on. The global PGD for the period 1972–2011 was −139%.

In the case of China a continuous and strong intergenerational materialization process is registered from 1999, probably as a result of the economy opening process which necessarily implies increases in energy consumption, as China joined the World Trade Organization (WTO) in 2001 (see Fig. 11). The total value of the PGD was −151.62%. The same applies to India, where the generational materialization persists along all the periods under study (−82.93%). The intergenerational materialization processes of China and India may have been due to reductions in the historically high rate of growth of population in a context of economic growth and then, growing energy consumption. According to Orgaz et al. (2011) the rate of growth of BRICS economies have been inferior to the global one from 2000, and therefore their weight in worldwide economy has remained constant from 1960 around 43%. In particular, according to data from World Bank, the population rate of growth in China fell from 2.75% in 1971 to 1.36% in 1976 and 0.48% in 2010; in India there is also a decreasing trend, but not as pronounced as in China, 2.37% in 1977 to 1.39 in 2010.

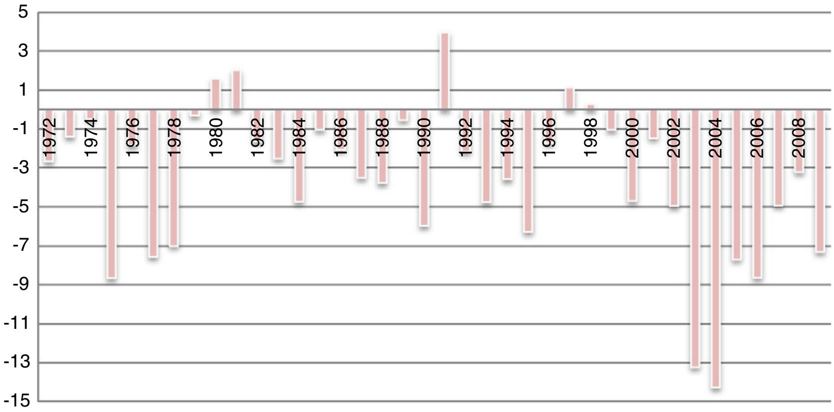
Finally, in order to deal with the key question of this research, we study product generational dematerialization of energy use for global economy (Fig. 13). We found only two medium-term dematerialization periods (positive values of the indicator for more than 3 years): 1980–1983 and 1990–1994, and two short term dematerialization episodes in 1974–1975 and 1997–1998. For the rest of the time period, global economy seems to have *materialized* from a generational viewpoint. The highest dematerialization values were found in 1982 (2.73%) while the highest materialization happened in 1976 (−4.13%) and 2010 (−4.42%). (See Fig. 13.)

Somehow our results contradict those of Ziolkowska and Ziolkowski (2011). While the results of the authors showed a general dematerialization for crude oil in global economy of 11.82% for the period



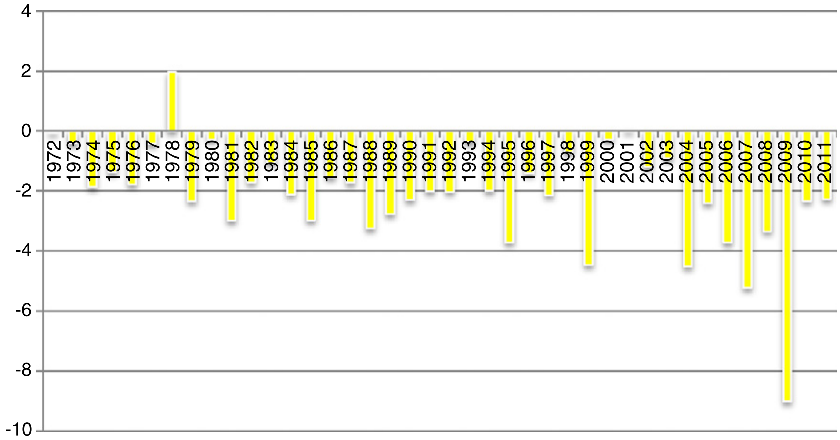
Source: Calculated based on Economic Policy & External Debt and Climate Change World Bank Database

Fig. 10. PGD indicator for energy use in the LA&C economies in 1971–2011 (in %).
Source: calculated based on Economic Policy & External Debt and Climate Change World Bank Database.



Source: Calculated based on Economic Policy & External Debt and Climate Change World Bank Database

Fig. 11. PGD indicator for energy use in China in 1971–2011 (in %).
Source: calculated based on Economic Policy & External Debt and Climate Change World Bank Database.



Source: Calculated based on Economic Policy & External Debt and Climate Change World Bank Database

Fig. 12. PGD indicator for energy use in India in 1972–2011 (in %).
Source: calculated based on Economic Policy & External Debt and Climate Change World Bank Database.

1972–2010, we found a general materialization for total primary energy sources that amounted to −18.30%. These contradictory results can be explained by the different indicators used for human environmental pressure. While Ziolkowska and Ziolkowski (2011) use oil crude consumption as a proxy of resources, we use total energy use, including all primary energy sources in order to avoid the impacts of potential substitutions between different energy sources on the indicator. According to information from the OECD/IEA (2013), in the period 1973–2010, the share of crude oil in TPE of the world reduced from 46.1% to 32.4% while coal increased from 24.6% to 27.3% and natural gas augmented from 16% to 21.4%. The same trend can be found in OECD where crude oil dropped from 52.6 to 36.3. Moreover, for a global dematerialization study, the composition of the energy matrix of China is crucial, as this country boosted its participation in total energy consumption from 7% in 1973 to 19.1% in 2010, and in this country, crude oil only represents 16% of TPE, while coal and peat account for 67%.

Considering the relevance of population growth for the PGD definition, future projected trends must be taken into account in order to analyze the potentials for intergenerational dematerialization. By mid-2012 world population reached 7.06 billion, with developing regions accounting for nearly 90% of demographic growth, particularly China and India (despite the recent reductions in historical growth mentioned above). The driving forces for the increase in population in developing regions are high birth rates and young populations. In this sense, as stated by Haub (2012)[10] even though birth rates are falling in some developing countries, they are expected to remain above replacement levels for the next decades in many regions, particularly in Asia. However, according to the IIASA scenarios, population will peak by 2050 and then reduce to the end of the century. Most of the population reductions after 2050 are expected to happen in Europe and China (which may be highly relevant for energy consumption projections if increases in GDP per capita do not compensate these reductions), while most developing regions are supposed to increase their populations: Africa and the Middle East will double, and LA&C and Central Asia will increase by 50% (Yeager et al., 2012).

Discussion and concluding remarks

One of the main contributions of this article has been the integration of two methodologies in order to analyze the sustainability of energy path from a wide, historical and dynamic perspective. While the phase diagram reflects the dynamic of the reduction (or increase) in energy

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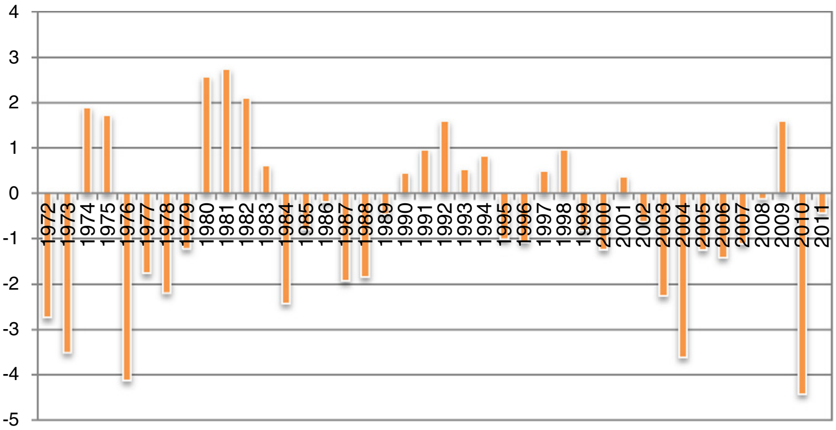
[10] See: www.prb.org/Publications/Datasheets/2012/world-population-data-sheet/fact-sheet-world-population.aspx.



Source: Calculated based on Economic Policy & External Debt and Climate Change World Bank Database

Fig. 13. PGD indicator for energy use in the global economy in 1971–2011 (in %).
Source: calculated based on Economic Policy & External Debt and Climate Change World Bank Database.

use per activity level, the PGD analyses the dynamic of energy consumption relative to population. In conjunction both instruments help to study the evolution of two of the most important determinants of energy consumption and environmental pressure. It is very important to remark that this study was performed through a *top-down* perspective and that future extensions of this analysis should be developed from a *bottom-up* standpoint in order to determine the sectorial potentialities for these countries and regions to develop different mitigation policies.

The second aspect to be remarked is that, despite the reductions in energy intensities in some regions, energy consumption and the consequent environmental impact display a growing trend for all regions and countries. There is one clear difference between the developed region and the developing ones. While in the former the rate of growth of energy consumption and CO_2 emissions is decreasing, both variables display an increasing rate of growth in all the developing regions, especially China. This aspect may be directly related to the evolution of two of the most important determinants of energy demand. On the one hand, despite the more recent trends and projections, most developing regions have been characterized by increasing population trends and as stated in the energy scenarios of IIASA, "*population growth is a modest to strong driver of energy demand*". On the other hand, as stated by Yeager et al. (2012) there is a wide consensus that income elasticity of energy demand is positive, but it differs according to the stages of development of the regions: at lower levels of economic development the income elasticity for energy demand is low, it is significantly high at medium levels, and finally it reduces at high levels of development (Yeager et al., 2012). The conjunction of these two characteristics implies an increased demand for energy services in developing economies, especially if the economic development path is accompanied by increases in disposable income: "*the income effect in terms of GDP and GDP per capita is positive and generally larger in developing countries, where small improvements in per capita income translate into an over proportional use of energy services*" (Yeager et al., 2012; 396). Therefore the projections for future increases in energy demand, and consequently environmental impact for developing regions are highly relevant. As mentioned in the GEA 2012, the future dynamics and influence of the developing regions, especially the BRICS, will be critical in shaping global energy demand as well as climate change mitigation trends. Nonetheless, despite the positive trend of the variables, these developing regions still maintain a low global energy consumption and energy consumption per capita in relation to the OECD region. The future development process will demand high investments in energy infrastructure, which could imply an opportunity for low-carbon energy development (Yeager et al., 2012; 395).

Thirdly, the results do not support the intergenerational *dematerialization* hypothesis. We did not find evidence for long term product generational dematerialization for any of the groups of countries under study. This situation is even more pronounced in developing regions such as China, LA&C countries and India despite the reductions in the rate of population growth. Moreover, from a wider perspective global economy seems to have *materialized*, following an unsustainable energy path, in the majority of the period under analysis. In the suited time period, materialization of total primary energy occurred more frequently and maintained for a longer time than dematerialization.

In this context, the role and potential of energy efficiency and reductions in energy consumption via national and international policies become crucial. Along the last decades, the growing environmental concern increased the debate about new policies on the reduction in energy consumption. Although the existing international institutional framework does not establish binding commitments for most developing regions (non-Annex 1 parties to the UNFCCC), this context is changing as the share of developing regions in GHG is augmenting and they are responsible for nearly 50% of CO_2 emissions (OECD/IEA, 2012). Along the last years there has been an increasing pressure for some developing countries, such as China, India, and some LAC countries to adopt some targets, under the current climate negotiations toward a post Kyoto agreement. This situation has intensified during the last Conferences of the Parties and has driven to the attention new instruments for mitigation purposes in developing countries, such as the National Appropriate Mitigation Actions (NAMAs).

However, as it is being discussed since the United Nations Climate Conference at Copenhagen,[11] the key point for developing regions will be how to promote socio economic development (which necessarily will augment energy demand) without increasing pollution.[12]

There are certainly different non-pollutant alternatives for economic growth, but they may demand more financial and technological resources. Therefore, the increased opinion in developing and underdeveloped regions relates to the historical responsibilities on emissions,[13] and the consequent demand to developed nations for financial support for their adaptation, mitigation and reforestation efforts. The commitment

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[11] For a complete debate on these topics see: Dutt (2009); Dutt (2010).

[12] This idea is present in most of the debates between developed and developing regions and as materialized in the concept such as Low Emission Strategies (LEDS) or Low Carbon Strategies (LCD).

[13] This is the debate on the historical responsibilities on GHG and the *Principle of Common but Differentiated Responsibilities*.

to reduce intensity of emissions in developing world will demand financial reward from the developed one. The existence of this type of financial support, as well as technological and knowledge transfers, will be crucial. As shown by Larson et al. (1986) and Williams and Larson (1986) (among others) technological improvements, public awareness and education were crucial for material decoupling, and it could also play a key role for energy decoupling. This will depend on the development of successful public policies implemented by national governments and supported internationally.

Lastly, there are still a lot of questions arising for the existence of a future energy sustainable path. Which will be the real impact of the economic-environmental measures that have emerged in the last decades? Will these initiatives induce global *de-coupling* and *de-carbonization* of the economies? Which will be the real environmental and socioeconomic impacts of a new international framework in which developing countries must commit to undertake mitigation actions? There is no unique and clear answer to any of these questions. The outcomes will depend on political decisions of policy makers as well as current and future institutional frameworks that will be arising.

Appendix A. Data and sources

Table A1
List of high income OECD countries.

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Israel
Italy
Japan
Korea, Rep.
Luxembourg
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Slovenia
Spain
Sweden
Switzerland
United Kingdom
United States

Table A2
List of Latin American countries.

Antigua and Barbuda
Argentina
Aruba
Bahamas, The
Barbados
Belize
Bolivia
Brazil
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Curacao
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Sint Maarten (Dutch part)
St. Kitts and Nevis
St. Lucia
St. Martin (French part)
St. Vincent and the Grenadin
Suriname
Trinidad and Tobago
Turks and Caicos Islands
Uruguay
Venezuela, RB
Virgin Islands (U.S.)

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