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THE ENERGY-ECONOMIC GROWTH RELATIONSHIP: A NEW INSIGHT FROM THE EROI PERSPECTIVE

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In the present paper we relate the recent estimations of the historical (1800-2011) global EROI of fossil fuels production performed by Court and Fizaine (2015) to the tremendous increase in Gross World Production that the global economy has encountered during the same period. We first show that on this entire period of study, there is a power inverse relationship that exists between the average price of aggregated fossil energy and its EROI. More precisely, we find that this long-term relationship is constituted of short-term relations that shift over time. We interpret these shifts as short-term cycles of EROI decrease/price increase/innovation to higher EROI. Furthermore, on the more restricted 1950-2011 time period on which we have continuous year-to-year data, we find a clear correlation between the EROI level of aggregated fossil energy and the growth rate of the Gross World Production (GWP). With the same data, we are also able to show that in order to have a positive growth rate, the global economy cannot afford to allocate more than 15% of its GWP to energy expenditures. In other words, this also means that considering the current energy intensity of the global economy, our primary energy system needs to have at least a minimal $EROI_{min}$ of approximately 6.5:1 (that conversely corresponds to a maximum tolerable average price of energy three times higher than current level) in order for the global economy to present a positive growth rate. From these different results, we then propose a business cycle model based on the EROI dynamics. Our study supports the idea that a coherent economic policy should first of all be based on an energy policy consisting in improving the net energy efficiency of the economy. Doing so would lead to a "triple dividend": an increase of the global economy EROI (through a decrease of the energy intensity of capital investment), a decrease of the sensitiveness of the economy to energy price volatility, and a decrease of GHG emissions associated with fossil energy consumption.

JEL classification: N7, O1, O3, Q4, Q57

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1. Introduction

Despite an apparent political willingness to disengage industrialized economies from their dependence on fossil fuels, they seemed to have stayed on a business-as-usual track up until now. One would respond to this assertion by pointing the efforts that industrialized countries (OECD and IEA members) have accomplished to lower their oil dependence and enhance their energy efficiency after the two oil shocks of the 70's. However, to those important signals of societal vulnerability to fossil energy dependence, strategies at this time have mainly consisted in a substitution of oil for gas and nuclear energy (hence, other nonrenewable energy resources) and major transitions towards modern renewable technologies did not occurred. This logically raises some serious thoughts since many authors have emphasized that the increasing use of fossil fuels is the very source of the uptake of human organizations on the path of industrialization and subsequent service-oriented society, thanks to their abundance, high concentration and associated low energy cost of extraction (Hall and Klitgaard, 2012; Stern and Kander, 2012; Ayres and Voudouris, 2014); whereas others have warned on the finiteness of these resources (Hubbert, 1956; Campbell, 2013). Hence, if there is no doubt that sooner or later a transition towards a complete renewable energy supply will occur, either because of increasing fossil fuels productions costs following the qualitative depletion of resources, or thanks to better environmental policies designed to reduce greenhouse gases (GHG) emissions and mitigate the climate change, investigating quantitatively the relationship between energy availability and economic growth is an issue of primary importance. First, because the apparent decreasing quality of the fossil fuels supply (as shown by the increasing prevalence of unconventional fossil fuels production) is going to have an increasing importance on the amount of primary energy supplied to the economy. Second, because the consequences on economic growth of a transition towards the so called cleaner energy technologies (wind turbines, photovoltaic panels, biofuels, etc.) remain largely controversial (Fizaine and Court, 2015; Court et al., 2015).

The literature associated with the energy-economic growth relationship is mainly based on three streams of research: (i) econometric analyses of the energy price-economic growth relationship; (ii) econometric analyses of the energy quantity-economic growth relationship; and (iii) the biophysical paradigm and its practical approach of the economic system through net energy and Energy-Return-On-Investment (EROI) analyses. In section 2, after succinctly presenting the main results of the two mainstream econometrics approaches (energy prices-economic growth and energy quantities-economic growth relationships), we will present the interest of the biophysical economics point of view. We propose in section 3 a long-term (1800-2011) relationship between the average price of fossil energy and the EROI of the global fossil energy system produced by Court and Fizaine (2015). In section 4, we dive more profoundly in the EROI-economic growth relationship on the restricted 1950-2011 time period. We are able to estimate, taking into account the current energy intensity of the economy, the minimum level of EROI that the global primary energy system should present if we want the global economy to present a positive rate of growth. Based on these results, we propose in section 5 a narrative model based on the EROI dynamics to explain that the economy is characterized by irregular business cycles. Finally, in section 6 we conclude and draw some policy implications from our study.

2. Theoretical background

2.1 Energy prices-economic growth relationship

Initiated by Hamilton (1983), some twenty studies now exist that focus exclusively on the relationship between the energy price (mainly through the oil price) and economic growth (Katircioglu et al, 2015; Laardic and Mignon, 2008). Due to the asymmetric impact of the oil price on economic growth[1], the classical methods of cointegration are ineffective and more sophisticated methods must be used to assess the energy price-economic growth relationship (Laardic and Mignon, 2008; An et al, 2014). In addition, the poor availability of data related to energy prices (across different countries and over time) complicates the assessment of this relationship. In a nutshell, this literature seems to converge toward a feedback relationship between energy price and economic growth variation (Hanabusa, 2009; Jamil and Ahmad, 2010), ranging from a negative to a positive effect depending on the level of oil dependency of the country under study (Katircioglu et al, 2015); and a clear negative inelastic impact of the oil price on the GDP for net oil importing countries. In addition, Naccache (2010) has shown that the impact of the energy price on economic growth depends on the nature of the oil price shocks (supply, demand or pure speculative based shocks), taking account of the fact that the relative importance of each of these factors has considerably varied over time (Benhmad, 2013). Furthermore, when performing our literature review, we found that all these studies consider that the oil price can impact an economy in a similar way between two dates, whereas during the same period of time the energy intensity of this economy can obviously really differs. In the same way that studies adequately assume that low and high energy intensity countries would not react exactly the same when facing an increase of the price of energy (because the former is clearly less vulnerable), that point should also be taken into account for a given country studied at different times. Hence, we recommend introducing the energy intensity as a key variable in future temporal empirical assessments of energy price-economic growth relationships.

2.2 Energy quantities-economic growth relationship

Another impressive flow of studies focuses on the relationship between the energy production quantities and economy growth. Such studies have been conducted since the seminal paper of Kraft and Kraft (1978). From this energy quantity-economic growth nexus, four assumptions have been envisaged and systematically tested:

- A causality from energy to economic growth. Under this assumption, energy conservation policies could compromise economic growth. The studies supporting this assumption are very close to the line of thoughts of the biophysical movement (presented in the following section) and the peak oil partisans, because it brings credit to the central role played by energy in the economy system.

[1] The asymmetric response of the economy to the variation of the oil price can be explained by different factors such as: the monetary policy, the existence of adjustment costs, the presence of uncertainty affecting investment choices and the asymmetric response of oil-based products to oil price variations. In the case of an oil price variation, the different adjustment costs can come from sector shifts, change in capital stock, coordination problems between firms, and uncertainty. When combined, these adjustment costs can completely erase the benefits associated with a decrease of the oil price. See Laardic and Mignon (2008) but also Naccache (2010) for more information.

- A causality from economic growth to energy. In this situation, energy is not essential and energy conservation policies can be pursued without the fear of any detrimental effects on economic growth. This conservative view reflects the position of many neoclassical economists for whom energy is seen as a highly substitutable minor factor of production.
- A feedback hypothesis between energy and economic growth.
- The absence of causality between energy and economic growth, an hypothesis also known as the neutrality assumption.

Unfortunately, after more than forty years of research and despite the increasing complexity of econometric studies, this area of study has not lead so far, neither to a general methodological agreement, nor to the preference for one of the four positions previously presented. More precisely, two independent studies (Chen et al, 2012; and Omri, 2014), integrating respectively 39 and 48 analyses, have shown that no particular consensus has emerged from this empirical literature and that the share of each assumption range from 20% to 30% of the total. These mixed results can be explained by different reasons, which include the period studied, the countries retained (the level of development affecting the results), the level of disaggregation of the data (GDP or sectorial levels), the type of energy chosen (total energy, oil, renewable, nuclear, primary vs. final energy), the econometrical method selected (OLS, cointegration framework, VAR, VECM, time series, cross and panel analysis), the type of causality tests employed (Granger, Sims or Toda & Yamamoto tests), and the number of variables included in the model (bi or multivariate model) (Kocaaslan, 2013; Huang et al, 2008ab; Wandji, 2013).

2.3 Biophysical economics, net energy, and EROI

<u>The biophysical paradigm</u>

In spite of this lack of consensus regarding the direction of econometrics causality tests between energy quantity and economic growth, we think they cannot be used to invalidate the importance of energy in economics. Indeed, suppose that we try to determine the importance of the quantity of energy needed for the acceleration of a truck by examining the causality between these two variables. If we proceed to a Granger causality test between the acceleration of the truck and the fuel bills, it would probably lead to a causality relation of the first to the second. But nobody can reasonably make the assumption that energy does not occupy the primary role in the increase of the speed of the truck, and that we can cut the consumption of energy without affecting its acceleration. This reasoning reinforces the point of view of the third stream of thought on the energy-economic growth relationship that regroups the various researches of the Biophysical Economics movement. As synthetized by Cleveland (1987), through an early and continuous effort, several thinkers have emphasized that the increasing complexification of human societies has been closely linked to their ability to control an increasing amount of energy (Podolinsky, 1880; Spencer, 1880; Ostwald, 1911; Lotka, 1922; Soddy; 1926; Cottrell, 1955). Then, two pioneering scholars, Georgescu-Roegen (1971, 1979) and Odum (1971, 1973), have ingeniously started to apply the thermodynamics laws and energy accounting principles to the analysis of the economic system during the 70's. Unfortunately, it is not these seminal studies that have alerted economics scholars and the public opinion on the dependence of the economy to its energy supply, but rather the tremendous negative impacts on economic growth that the two oil shocks have generated at the same period. Nevertheless, researchers in this field have then pursued their effort

(Cleveland et al., 1984; Hall et al., 1986) up to very recent synthetizes (Hall and Klitgaard, 2012; Ayres and Warr, 2009; Kümmel, 2011).

In parallel of the calls for a broad paradigm shift in economics (Faber, 1985; Hall et al., 2001; Hall and Klitgaard, 2006), biophysical approaches of the economy have been developed in pure conceptual papers related to entropy and sustainability (Perrings, 1987; O'Connor, 1991; Ayres, 1998; Krysiak, 2006) [2].From an applied point of view, these researches have particularly focused on the Energy-Return-On-Investment (EROI) of the different energy forms that humans use. Although these analyses fruitfully highlight the centrality of energy in economics, there has been up until now a lack of analytical and quantitative studies focusing on the relationship between the EROI and economic growth. Two exceptions to that point are the GEMBA model of Dale et al. (2012) and the endogenous economic growth model of Court et al. (2015).

From the net energy to the EROI

The concept of net energy was first enunciated by Odum (1973) when he stressed that it is not sufficient to look at the quantitative volumes of energy that are available, i.e. stock and flow resources, because the most important variable is the quantity of energy that is really available to society once the energetic system has been supplied for its own energy need. For Odum (1973) "the true value of energy to society is the net energy, which is that after the energy costs of getting and concentrating that energy are subtracted". Following this idea, Lambert et al. (2014) have proposed a hierarchy of energy needs (Figure 1) that is analogous to Maslow′s hierarchy of human needs (Maslow, 1943). In this view, needs perceived as "lower" in the hierarchy, e.g. extraction and refining of gross energy, must be satisfied before needs "higher" in the hierarchy become important at a societal level. In other words, energy use for the "highest" needs, i.e. performing arts and other social amenities, are perceived as a societal energetic necessity only once all levels beneath them are fulfilled (Lambert et al., 2014).

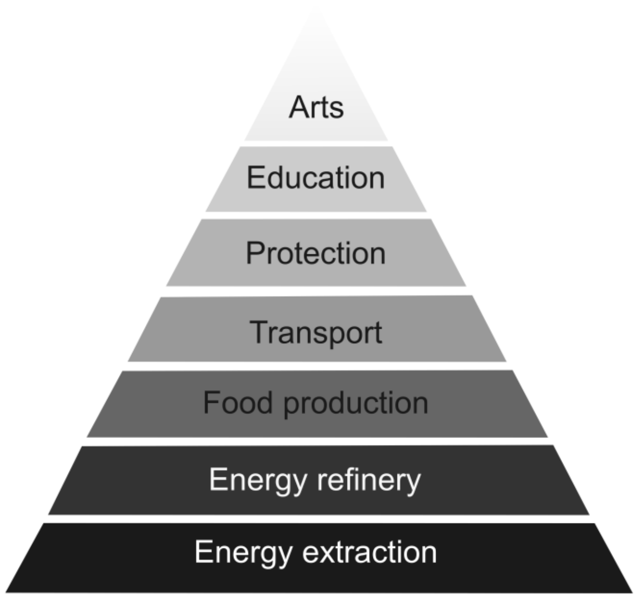


Figure 1. Hierarchy of Energetic Needs. Source: adapted from Lambert et al. (2014).

[2] This theoretical work ultimately led to the *Ecological Economics* stream of thought and the establishment of its representative international society in 1987 and academic journal of the same name in 1989.

Furthermore, the access to a “higher” energy need requires for the energy resource in use to deliver sufficient net energy surplus. For example, one can only spend energy on health care if there is enough net energy left after “lower” energy needs have been fulfilled (extract, refine and transport energy and food, built shelter, educate people).

Energy gain, energy yield, energy surplus are all more or less equivalent terms found in the literature that are more formally defined by the Energy-Return-On-Investment (EROI). The EROI expressed in equation (1) is a derivative concept of net energy and was formally introduced by Cleveland et al. (1984) with the following formal definition:

$$EROI = \frac{Gross\ Energy\ Produced}{Energy\ Invested\ to\ get\ that\ Energy} \tag{1}$$

The net energy and the EROI are logically related according to equation (2):

$$Net\ Energy = Gross\ Energy\ Produced * \left(1 - \frac{1}{EROI}\right) \tag{2}$$

The EROI is a unitless ratio used to compare outputs to inputs and is therefore more convenient than net energy, which is a finite amount of energy (Murphy et al, 2011). An EROI ratio of “20:1” has to be read “twenty to one” and implies that a particular process or energy resource yields 20 Joules on an investment of 1 Joule (and consequently delivers 19 Joules of net energy). Informations related to the methodology of calculation of an EROI can be found in the appropriate literature: Herendeen 2004; Cleveland, 2005; Mulder and Hagens, 2008; Murphy et al., 2011; Brandt and Dale, 2011; Brandt et al., 2013.

Because of the lack of hindsight regarding renewables and unconventional fossil fuels productions (such as shale oil, heavy oil, tar sands, shale gas, etc.), time-series of EROI have been calculated only for conventional fossil fuels resources and at national scale[3]. The only EROI study of international scope is the one of Gagnon et al. (2009) for the global oil and gas production between 1992 and 2006. Furthermore, such analyses have been conducted on short or mid-term time horizons only (few decades at most). A notable exception to this fact is the EROI assessment of the American oil and gas industry from 1919 to 2007 performed by Guilford et al. (2011). The results of these studies are synthetized in Lambert et al. (2012) and Hall et al. (2014), they all show declining trends in recent decades with maximum EROI already reached in the past. As society turns necessarily towards lower quality conventional fossils fuels and unconventional fossil fuels, more and more energy is invested in the energy-extraction sub-system of the economy, making net energy delivered to society less available and fuels more expensive. For these reasons, but mostly for geostrategic reasons and the pollution associated with the use fossil fuels, political and scientific attention is increasingly being paid to renewable sources of energy. Unfortunately, EROI analyses have shown that so far renewable technologies do not generate as much net energy as fossil energy used to do so (Murphy and Hall, 2010; Lambert et al., 2012; Hall et al., 2014). Furthermore, as stated by Fizaine and Court (2015) the EROI of renewable electricity producing technologies is more sensitive than fossil fuels EROI to the increasing energy cost associated with the extraction of the numerous common and rare metals incorporated in their construction. Hence for now, performing an energy transition towards renewable technologies seems to necessarily imply a

[3] Time series of EROI values for fossil fuels found in the literature review of Lambert et al. (2012) and Hall et al. (2014) concern the following productions: American oil and gas, Canadian oil and gas, Norwegian oil and gas, Mexican oil and gas, Chinese oil, gas and coal, Canadian dry gas and American dry gas.

shift from a high to a low EROI supply energy mix (i.e. a decrease of the societal EROI). This pattern will have consequences on society that remain unclear, but it necessarily raises some serious concerns since our industrialized complex societies have been built on the use of high quality fossil energy resources and that the dependence of the economy to its fossil energy supply can have huge adverse effects on its capacity of development (Court et al., 2015).

These facts have already been discussed in larger discussion regarding the potential for long term sustainable development of modern societies but those were essentially qualitative (Hall and Day, 2009; Hall et al., 2009; Murphy and Hall, 2010, 2011a, 2011b; Lambert et al., 2014). The recent work of Court and Fizaine (2015) in which historical energy prices and global EROI of fossil fuels (coal, oil, and gas) are estimated from 1800 to 2011 should now bring more quantitative understanding on the role of the net energy constraint on economic growth. In this work, a price-based approach is used to calculate the different EROI, before being comforted by a theoretical dynamic model of the EROI. The different methodologies logically deliver different results, but it can be fairly advanced that: (i) the global maximum EROI for oil and gas have already been reached in the past, respectively around 73:1 in 1930 and 200:1 in 1945; (ii) the maximum global EROI for all aggregated fossil fuels has also been reached around 65:1 in 1965; (iii) global coal production has not reached its maximum EROI yet; (iv) Without any possibility of higher precision, the maximum global coal EROI will most probably occur around 2030 with a value about 110:1. In Figure 2 and 3 below, we reproduce from this study the global average price of aggregated fossil energy and the global EROI of the total primary fossil energy sector that we are going to use as input data in the present study (see Court and Fizaine, 2015 for more details on the methodological aspects and results for the different fossil fuels EROI).

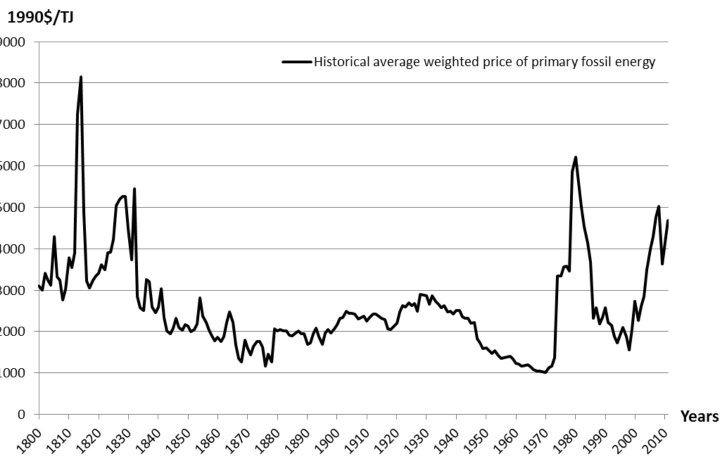


Figure 2. Estimation of the global constant 1990$ average price of fossil energy weighted by the production quantities of each fuel (coal, oil, and gas) from 1800 to 2011. Source: Court and Fizaine, 2015.

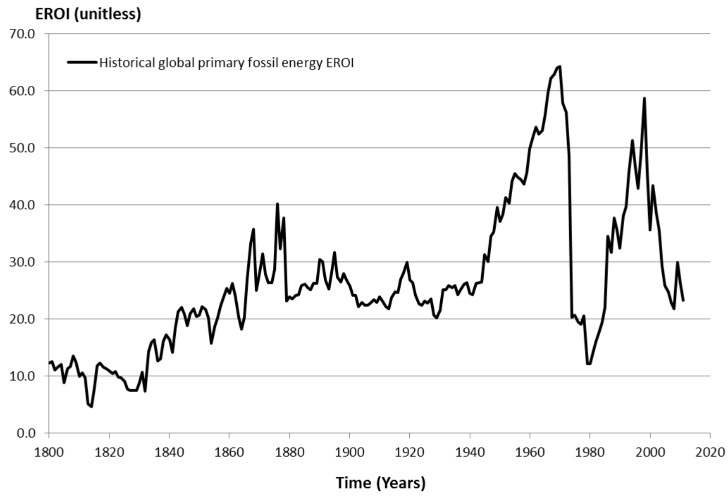


Figure 3. Estimation of the EROI of the global primary fossil energy sector from 1800 to 2011. Source: Court and Fizaine, 2015.

3. EROI-energy price relationships in the short and long-term

Using the data previously exposed, we find that when the global EROI of the primary fossil energy system is plotted against its global average weighted price, the scatter plot presents a form that roughly follows a power inverse relationship (Figure 4). This result is in line with King and Hall (2011) and Heun and de Wit (2012) who have found the same relation between the EROI and the price of US crude oil on shorter time periods.

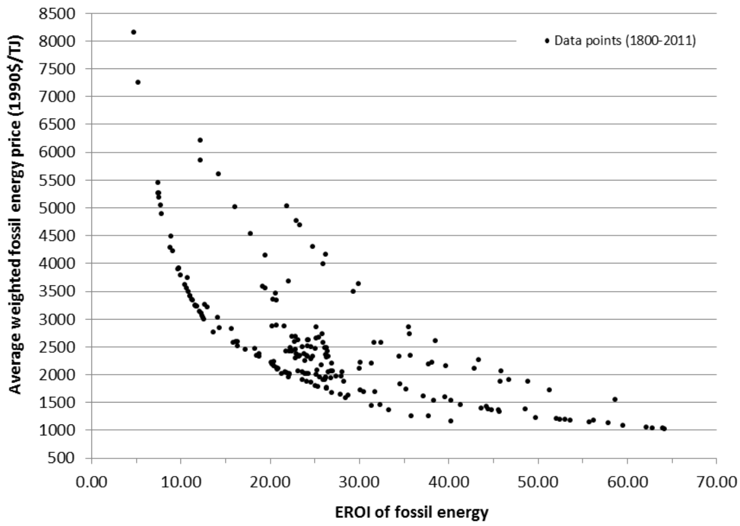


Figure 4. Relationship between the estimated global EROI of the primary fossil energy sector and the global average weighted price of fossil energy with a continuous set of data from 1800 to 2011 retrieved from Court and Fizaine (2015).

This relationship between the global EROI of fossil energy and its average weighted aggregated price can be precised if we follow the course of the time between the points of the Figure 4. When doing so, we find that the overall relationship of Figure 4 is in fact constituted by a succession of short term relationships. This is shown in Figure 5 where we present the exact same data as Figure 4 to which we only add a “color segmentation” whenever the direction of time changes between 1800 and 2011.

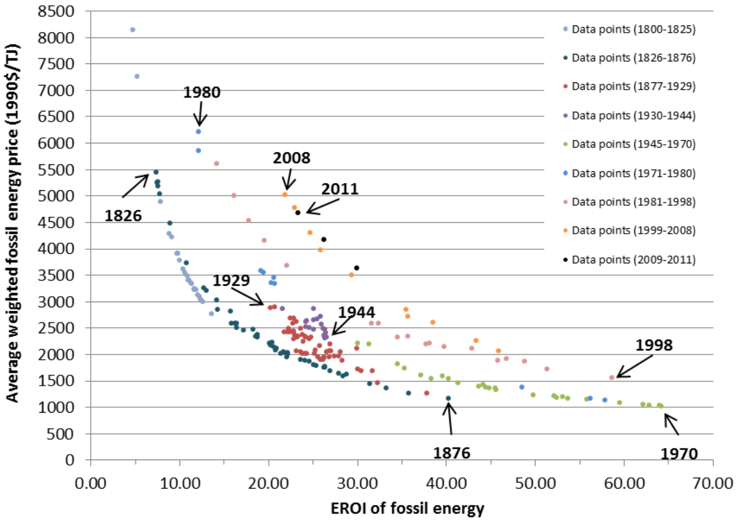


Figure 5. Relationships between the global EROI of the primary fossil energy sector and the global average weighted price of fossil energy with a temporal segmented set of data from 1800 to 2011 recovered from Court and Fizaine (2015).

The Figure 5 clearly shows that over time, there are temporal shifts of the global relationship previously presented in Figure 4, that can moreover present different temporal directions. The successive temporal shifts of the relationship between the global EROI of fossil energy and its price could, to our mind, be interpreted as different phases of successive business cycles. A decisive argument backing this assumption is to remark that all switching dates of the EROI-energy price short-term relationships (1876, 1929, 1968, 1980, and 1998) correspond almost exactly to different global economic crises of the economic history[4]. The first switch (1876) corresponds to the "long depression" at the end of the nineteenth century. The second switch (1929) perfectly matches the great depression of 1929 that lasted up until World War II (WWII). The third switch (1970) marks the (near) end of the greatest global growth period following WWII. A short time later, the fourth switch (1980) arises after the second oil crisis. Finally, the last switch (1998) illustrates the Asian crisis. It is worth noting that the 2007-2008 financial crisis induces a shock in the relation (the fossil energy price decreases abruptly) but with no change in the direction of time, so no new short-term relationships appears. One can furthermore observe in Figure 5 that periods of decreasing price-increasing EROI (1826 to 1876, 1945 to 1970, 1981 to 1998) alternate with periods of increasing price-decreasing EROI (1877 to 1929, 1971 to 1980, 1999 to 2008). The 1930-1944 time period is more confused with the price and the EROI of fossil energy oscillating around average values (respectively 2500 1990$/TJ for the price and 25:1 for the EROI) without any clear trend. Nevertheless, this alternating pattern that we have identified, clearly supports the idea of successive business cycles. Those would primarily be composed of two phases: the first one corresponding to a period of high or increasing growth rate of the Gross World production (GWP) (1826 to 1876, 1945 to 1970, 1981 to 1998), whereas the latter

[4] It is important to point out here that it would be extremely inappropriate to produce econometrical estimations of these short-term relationships. Indeed, the fossil energy EROI presented in Figure 3 and used in Figure 4&5 were estimated with a methodology based on the fossil energy price estimation presented in Figure 2, and also used in Figure 4&5. That is why an apparent extremely good fit to an inverse power function can be seen for the short-term relationships in Figure 5, but estimating the coefficients of determination and the parameters values of these functions would be incongruous because of a clear methodological endogeneity. Nonetheless, this fact does not preclude observing that the direction of time changes along these short-term relationships, and that the particular shifting times correspond to major historical economic events. We should also not be prevented to comment these facts and try to find their underlying mechanism.

corresponds to times of low or decreasing growth rate of the GWP (1877 to 1929, 1971 to 1980, 1999 to 2008). The importance of the EROI in the mechanisms of those business cycles will be precised in the following of the paper in section 5, but let us stand for now that the economic growth dynamics also primarily depends on the dynamics of the energy intensity of the global economy that has greatly decreased from 1800 to 2011 as presented in Figure 6.

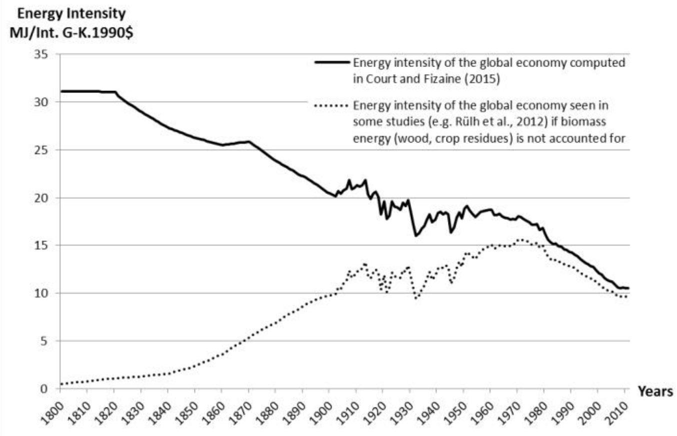


Figure 6. Energy intensity of the global economy from 1800 to 2011 retrieved from Court and Fizaine (2015) where a comparison with values seen in other studies like Rülh et al., 2012 is shown when traditional biomass energy (wood, crop residues) is not accounted for.

We have schematized in Figure 7 three consecutive periods observed in Figure 5. Hence in Figure 7, the different points (1), (2), and (3), could respectively be identified as the year 1877, 1945, and 1980. When within such a business cycle, the fossil energy price gradually increases from p_1 to its higher value p_2, which logically triggers in return a decrease of the energy consumption level that accelerates as p_2 is approached. After a while, since the energy price p_2 cannot be sustained by the economy, it decreases brutally to p_3. Yet, during the time period from point (1) to (2), increasing energy prices have induced economic incentives to develop energy efficient processes, in the production of energy itself but mainly in its consumption by the dissipative part of the economy. Hence, in comparison to the point (1), the economy in (3) presents a lower level of energy intensity and can thus support a higher fossil energy price thanks to a similar or slightly higher level of EROI. The process can continue as long as the technological progress is sufficient to mitigate the effect of the price increase and prevent the economy to reach a minimal level of EROI under which growth cannot be sustained (see the section 4.2 on the minimal sustainable EROI level). Therefore, one of the interesting results here is clearly the central role of the energy efficiency gains in the long term relationship between the global EROI of fossil energy and its associated energy price.

We have to keep in mind that the EROI and the energy price represent the two faces of the same coin that induce change in the level of energy expenditures of the economy, i.e. in the amount of GDP (or GWP at global scale) allocated to the procurement and use of energy. In the following section we further discuss the link that exists between energy and economic growth from this energy expenditures point of view.

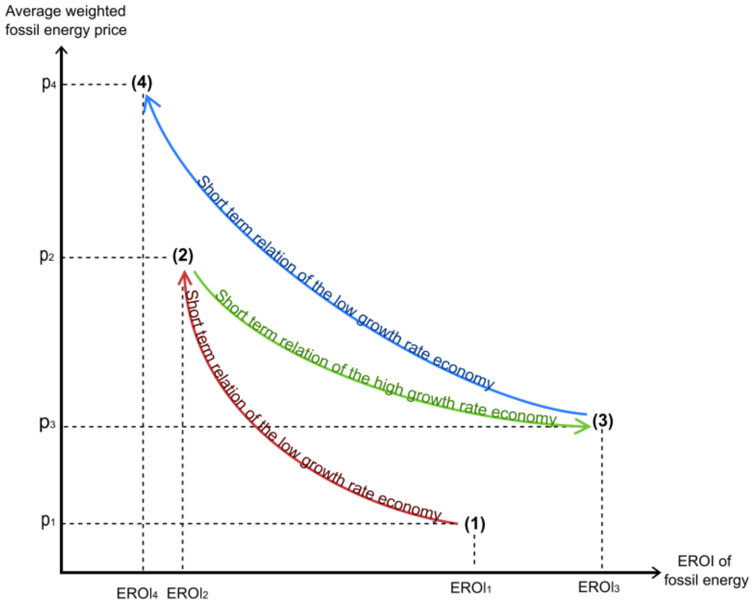


Figure 7. Schematization of the process underlying the temporal shifts of the relationship existing between the global EROI of primary fossil energy and its average weighted price.

4. EROI and economic growth

4.1 Energy expenditures as a limit to growth

As seen previously, the energy intensity of the economy plays an important role in both explaining the impact of the average fossil energy price on global economic growth, and defining the level of the global EROI of fossil energy. This is why we have tried to assess the impact on economic growth of the fossil energy price corrected by the level of the energy intensity. Let us first remarked that multiplying the fossil energy intensity of the economy (which is almost equal to the total energy intensity of the economy since fossil fuels have a preponderant share in the total primary energy mix) $EI_{Fossil} = E_{Out,Fossil}/GWP$ to the fossil energy price P_{Fossil} gives the level of fossil energy expenditures on the gross world production, $P_{Fossil} * E_{Out,Fossil}/GWP$. The role of this variable has been mentioned several times in the work of Murphy and Hall (2011a,b) suggesting that "when energy price increase, expenditures are re-allocated from areas that had previously added to GDP, mainly discretionary consumption, towards simply paying for more expensive energy". This fact is supported in Figure 8 in which we can see that on the 1970-2007 time period, whenever the petroleum expenditure of the US economy has been higher than 5.5% of its GDP, the American economy has been in recession.

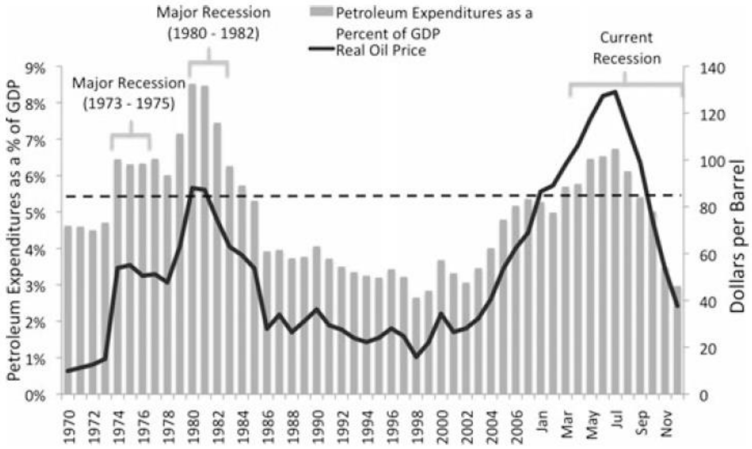


Figure 8. Petroleum expenditures as a percentage of GDP and real oil price ($/barrel). The dotted line represents the 5.5% threshold above which the economy moves towards recessions. Petroleum expenditures include distillate fuel oil, residual fuel oil, motor gasoline, LPG, and jet fuel. "Current recession" refers to the 2007 financial and then economic crisis. Source: Murphy and Hall, 2011a.

Hence, it seems possible to estimate the maximum energy expenditure level (as a share of GDP) that a given economy system should not exceed in order to have positive growth. As can be seen in Figure 9, using global scale data on GWP (recovered per capita from the Maddison project (2013), and hence multiplied to the United Nations (2015) population) and total fossil fuels expenditures (and not only petroleum), we found a decreasing relationship between the global economic growth and the level of fossil energy expenditures as a share of the GWP between 1951 and 2011 (we had to restrict our analysis to this time period because it is the only one with which we have uninterrupted year-to-year data for the GWP). The increase of the share of fossil energy expenditures in the GWP is a sufficient condition for a decrease of the world economic growth but this factor is not a necessary condition for a contraction of the economy since geopolitical, climatic and other socioeconomic events can also reduce economic growth. This explains why in Figure 9, the variance of the points is more important for lower levels of fossil energy expenditure shares of GWP (left side of the graph).

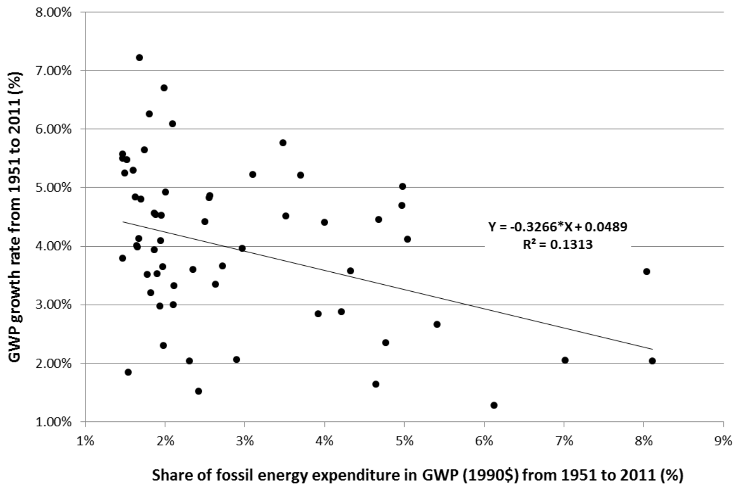


Figure 9. Estimation of the relation between the share of global fossil energy expenditures in the GWP and the global economic growth rate from 1951 to 2011.

The estimated equation of Figure 9 takes the following form:

$$g_{GWP} = \alpha - \theta \, \frac{P_{Fossil} * E_{Out,Fossil}}{GWP} \tag{3}$$

Where g_{GWP} is the global economic growth rate, α is the intercept taking the value 0.0489, P_{fossil} is the weighted average price of fossil energy, and θ represents the sensitivity of the global economic growth rate to the share of global fossil energy expenditures in GWP (taking the value 0.3266). An alternative specification is to take the GWP and the energy expenditure level as a share of the GWP in logarithmic forms, which allows estimating that the elasticity of the growth rate of the GWP to the logarithm of energy expenditure is -0.0105%. In other words, at the mean point, when energy expenditures as a share of the GWP increase by one percent (from 2.585% to 2.611%), the GWP growth rate decreases by 0.0105% (from 3.835% to 3.834%). Robustness checks of the econometric relation can be found in Appendix[5]. Off course, a more accurate estimation of the relation between the GWP and the energy expenditures level should include different control variables such as aggregated capital and labor. Unfortunately, due to the unavailability of such data on a global scale and on the time scale of the present study, we were able to only introduce the level of the American capital provided by the World Bank (2015). As shown in Appendix, this procedure does not change neither our conclusion about the impact of energy on growth, nor the level of this impact.

Furthermore, we performed some Granger causality tests to identify the direction of the possible causal relationship (from 1951 to 2008) between: the energy expenditures level of the global economy as a share of its GWP, and the growth rate of the GWP. There are many other causality tests based on different definitions of causality, but the main idea of the Granger causality test (1969) is to verify that adding past data of variable Y to past data of variable X enhances the prediction of present values of variable X. If the residuals generated from a model with variable X and its past only, and from another model with the past of variable X and Y are significantly different, we can reject the assumption of non-causality from Y to X and accept the assumption of a causality running from Y to X. Formally, it consists in running the following Wald test:

$$H_0 \colon \forall\, i \in [1, \dots, k], \gamma_i = 0 \; and \; H_1 \colon \exists\, i \in [1, \dots, k], \gamma_i \neq 0$$

$$X_t = \sum_{i=1}^{i=k} \beta_i X_{t-i} + \sum_{i=1}^{i=k} \gamma_i Y_{t-i} + \varepsilon_t \tag{4}$$

Our results presented in Table 1, show that we can reject the assumption that the level of fossil fuel energy expenditures as a share of the GWP does not Granger cause its growth at 1% of risk. Concerning the reverse relationship, the assumption that the level of fossil fuel energy expenditures does not Granger cause the level of energy expenditures (as a share of the GWP) can also be rejected with a 10% risk. In summary, these tests indicate a feedback causality between the two variables at 10% of risk and a causality running from the level of fossil fuel expenditures to the GWP growth rate with a 1% risk. The introduction of two exogenous dummies variables taking into account the two oil shocks drastically change the

[5] The reader will find: unit root tests (ADF) showing that the two series are stationary; White, Jarque-Bera and Durbin-Watson tests showing normality and homoscedasticity of residuals for the econometric regression of equation (3) and Figure 9; and various robustness tests of cointegration.

result and indicates a unique one way Granger causality running from the level of fossil fuel energy expenditures (as a share of GWP) to economic growth at 1% of risk (see Table 1). We get similar results with energy expenditures expressed in log, or when performing a three years central moving average on energy expenditures instead of introducing dummies for the two oil shocks. We have also performed a Granger causality test on a modified expression of (3) where growth is not dependent on GWP[6]. The results of these supplementary tests do not change our conclusions.

Table 1. Results of the Granger causality tests with different variables.

Null Hypothesis:	F-Statistic	Prob.	Lags
EX_GWP does not Granger Cause GROWTH	**9.119203*** **	0.0025	1 (AIC, SCH)
GROWTH does not Granger Cause EX_GWP	2.755157*	0.0969	1 (AIC, SCH)
EX_GWP + dummies does not Granger Cause GROWTH	**8.778937*** **	0.0030	1 (AIC, SCH)
GROWTH does not Granger Cause EX_GWP + dummies	0.093176	0.7602	1 (AIC, SCH)
EX_GWP CMA(3) does not Granger Cause GROWTH	**6.034048** **	0.0489	2 (SCH)
GROWTH does not Granger Cause EX_GWP CMA(3)	1.513628	0.4692	2 (SCH)
log (EX_GWP) CMA(3) does not Granger Cause D(logGWP)	**6.636128** **	0.0362	2 (AIC, SCH)
D(logGWP) does not Granger Cause log (EX_GWP) CMA(3)	0.913531	0.6333	2 (AIC, SCH)
D(EX) does not Granger Cause Detrend(GWP*(growth-α))	**4.939635** **	0.0262	1 (AIC, SCH)
Detrend(GWP*(growth-α)) does not Granger Cause D(EX)	2.316487	0.1280	1 (AIC, SCH)
D(EX) does not Granger Cause GROWTH	**7.21083*** **	0.0095	1 (AIC, SCH)
GROWTH does not Granger Cause D(EX)	2.70055	0.1059	1 (AIC, SCH)

* denotes 10% of risk, ** 5% of risk, ***1% of risk. AIC: Akaike info criterion, SCH: Schwarz info criterion. CMA (3): three years central moving average. D: first difference. Detrend: detrending. EX_GWP: Energy Expenditures on GWP, GROWTH: Growth of GWP, EX: Energy expenditures

Using equation (3), it is easy to find the particular value of the fossil energy expenditure (as a share of the GWP) that leads to a nil economic growth rate. In other words, we can define the maximum level of fossil energy expenditures (as a share of GWP) that the global economy can endure to still present positive economic growth. This specific value is called β, with:

$$\beta = \frac{\alpha}{\theta} = \frac{0.0489}{0.3266} = 0.1497 \tag{5}$$

Considering a 5% risk, we found that $0.085 < \beta < 0.215$[7]. This result means that if the share of fossil energy expenditure is higher than 15% of the GWP (with a 5% risk interval of [8.5%-21.5%]), economic growth does not occur at the global level.

4.2 Maximum energy price and minimum EROI tolerable by the economic system

Maximum tolerable aggregated fossil energy price

The result obtained previously that 15% is the maximum share of the GWP that can be allocated to energy expenditures in order to still have positive economic growth can be reformulated as the maximal fossil energy price $Pmax_{fossil}$ that the global economy can accept to still present a positive growth rate. Of course, this hypothetic maximum tolerable

[6] In that case the new expression of (3) is: $GWP \times (g_{GWP} - \alpha) = -\theta P_{fossil} * E_{out,fossil}$

[7] This range of values has been found with a coefficient restriction test led with a Wald Test.

price of the fossil energy depends on the level of the fossil energy intensity of the global economy as shown in (6) and in Figure 10.

$$Pmax_{Fossil} = \frac{\beta}{\frac{E_{Out,Fossil}}{GWP}} \tag{6}$$

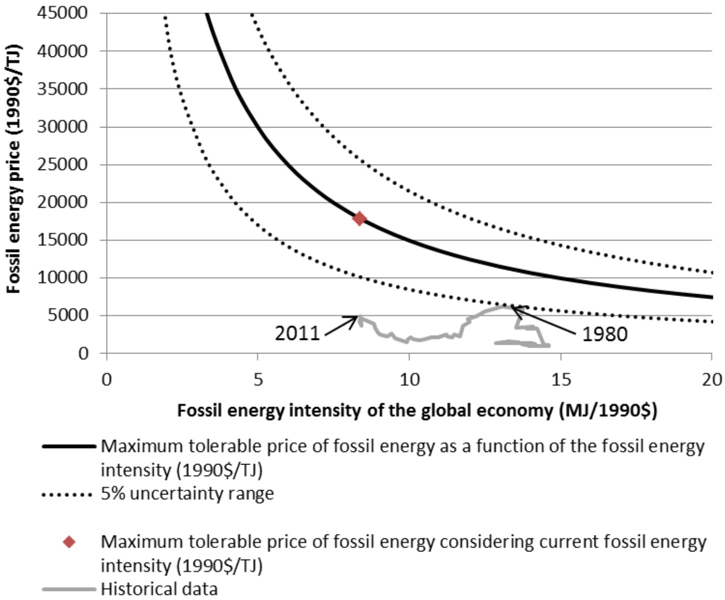


Figure 10. Maximum fossil energy price (1990$/TJ) that is tolerable by the global economy in order to have a positive growth rate of the GWP as a function of the fossil energy intensity of the economy.

As an example, let us consider the last point of our data, the year 2011, in Figure 10. With a fossil energy intensity of 8.4MJ/1990$, the global price of fossil energy would have had to reach 17870 1990$/TJ instead of its real historical estimate value of 4680 1990$/TJ[8], to annihilate the global economic growth. This shows that currently, the aggregated average price of fossil energy would have to be multiplied by 3.8-fold order of magnitude to imply a zero growth rate of the GWP. In the 80's, only a 2-fold multiplication of the aggregated fossil energy price would have vanished the remaining GWP growth rate of the time.

Minimum tolerable EROI

Let us now recall that following Court and Fizaine (2015), the global $EROI_{All\ Energies}$ of the economy (including the entire energy sector, i.e. nonrenewable and renewable energies) can be expressed as in (7) as a function of the weighted average price of energy $P_{All\ Energies}$, the average Monetary Return On Investment (MROI) of the global energy sector, the Gross World Production (GWP) and the total production of energy $E_{Out,All\ energies}$.

$$EROI_{All\ Energies} = \frac{MROI}{P_{All\ Energies} * \frac{E_{Out,All\ energies}}{GWP}} \tag{7}$$

[8] This price represents the last data of our series in 2011. Considering the recent fall of the oil price, the current weighted average fossil energy price is likely to be nearly 3000 1990$/TJ in 2015.

If we make the assumption that the average price of fossil energy is a good proxy for the average price of the primary energy (which is a rather good assumption since fossil fuels still represent 80% of the total primary energy supply and that it is impossible to compute $P_{All\ Energies}$ since it is impossible to give a price to renewable and nuclear energies when they are expressed in primary terms); we can replace $P_{All\ Energies}$ in (7) by the expression (6) of $Pmax_{Fossil}$. This also implies to make the further assumption that the value of β that we found as the maximum level of fossil energy expenditures that the global economy can endure, remains valid when we speak about energy in general and not only fossil energy. With all these assumptions, we obtain an expression of the $EROI_{Min}$, i.e. the minimal level of EROI that the global primary energy system must present in order for the global economy to have a positive rate of growth:

$$EROI_{Min} = \frac{MROI}{\beta * \frac{E_{Out,All\ Energies}}{E_{Out,Fossil}}} \tag{8}$$

The MROI used in Court and Fizaine (2015) is quite constant with and average value of 1.158 and a standard deviation of 0.020 on the 1800-2011 time period. Using this average value of 1.158 for the MROI, and the value of 0.1497 previously calculated for β, and taking into account that currently fossil energy represents 80% of the primary energy mix (value derived from the energy production data used in Court and Fizaine, 2015); we found that the global economy requires a primary energy system that presents an $EROI_{Min}$ of 6.5:1 in order to have positive global economic growth. Taking the uncertainty range with a 5% risk of β (0.085-0.215), and considering an MROI varying between 1.05 and 1.2, the sensitivity of the $EROI_{Min}$ range from 3.90 to 11.75 as shown in Figure 11.

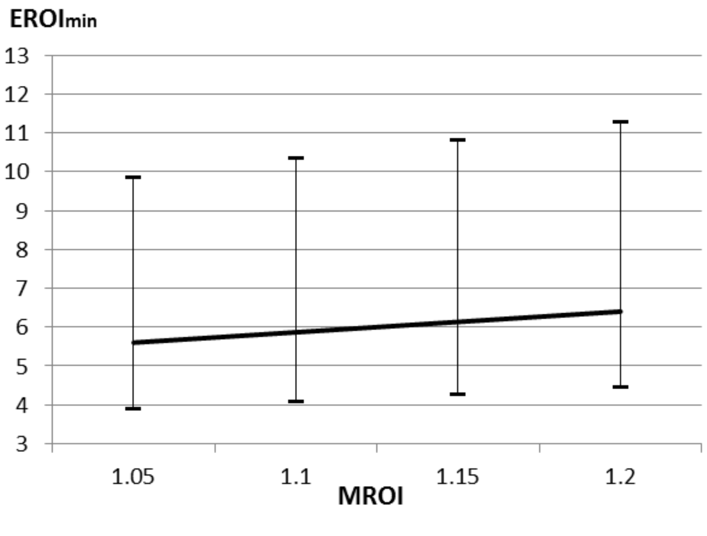


Figure 11. Sensitivity of the global $EROI_{min}$ to the MROI and to β with a 5% risk.

This estimation of the minimum EROI of 6.5:1 (with a 5% risk interval of [4-12]) that the global primary energy system must present in order for the global economy to have a positive rate of growth should be compared to the average EROI values that can be found for different energy systems. Indeed, if the fossil energy system is now presenting an average EROI of 25:1 at the global level (Figure 3), renewable energy technologies towards which humans' future is destined present relatively lower EROI, with average values[9] of 18:1, 6:1, and 1.5:1 for wind power, photovoltaic panels, and biofuels of first generation respectively (Hall et al., 2014). Only hydropower exhibits high EROI of about 50:1, but its global remaining potential will probably come to saturation in a few decades.

Let us summarize the results obtained so far in this paper: (i) the price and the EROI of fossil energy are connected by short-term relationships that shift over time in accordance to major economic events; (ii) the level of energy expenditures in the economy, i.e. the amount of GWP diverted to get energy, seems to play a limit to growth role since a Granger causality was found from the energy expenditures level towards the GWP growth rate; (iii) the global energy expenditure level cannot exceed 15% of GWP if the rate of growth of the economy is to remain positive; (iv) this can also be expressed has having a primary energy system that present a minimum EROI of 6.5:1, given the current energy intensity of the economy. In the following section, we propose a business cycle model that summarizes our previous results in a single narrative model.

5. Proposition of a business cycle mechanism based on the EROI

Before presenting the mechanism that we think underlies the economic growth process, let us first observe in Figure 12 the rather good correlation that exists from 1951 to 2011 between the growth rate of the GWP and the global EROI of the primary fossil energy sector.

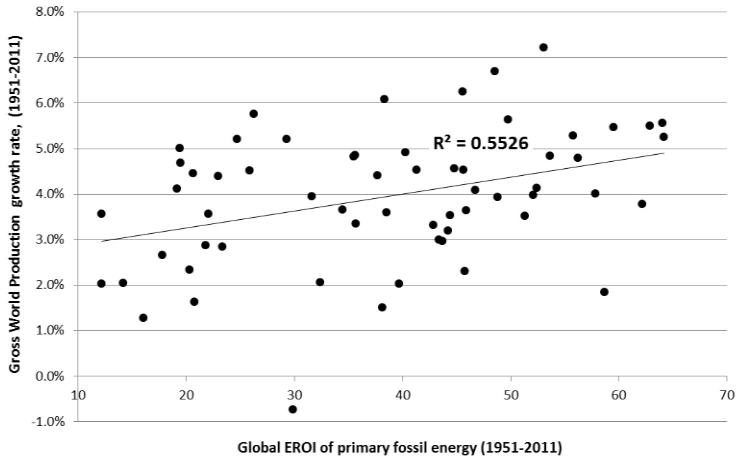


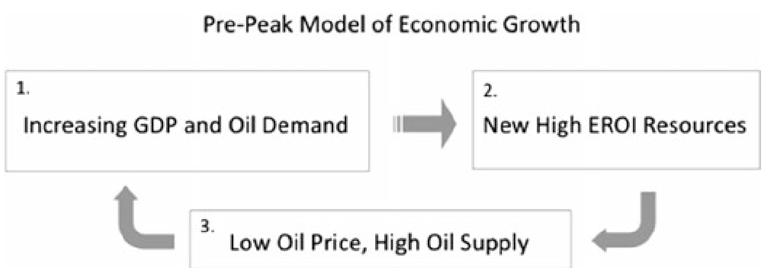
Figure 12. Correlation between the global EROI of the total primary fossil energy and the rate of growth of the Gross World Production from 1951 to 2011.

On a larger time frame, starting from nearly 12:1 in 1800, the EROI of fossil energy reached 25:1 in 1880 whereas at the same time the GWP growth rate increased from a level inferior to 0.5% per year to an average value of about 2% per year at the end of the nineteenth century. Likewise, the GWP has experienced its phase of highest growth rate (5% per year in average) from 1950 to 1973, while at the same time the EROI of fossil energy was also increasing the most (1.5% per year in average) and reached its maximum value of about 65:1 in 1970. A

[9]From a technical point of view, one will argue that there are no such things as « average EROI values » of a given energy type, especially regarding renewable energy technologies. Indeed, each individual energy system has a particular EROI. Hence, the different numbers given here must be understood as representative orders of magnitude.

very important fact is also that the global EROI of fossil energy began a decreasing phase three years before the oil shock of 1973, indicating that shocks on physical constraints induce economic fluctuations with delays.

The correlation previously presented in Figure 12 between EROI levels and economic growth rates at the global level, the relationship between the EROI and the energy price exposed in Figure 5 of section 3, and the relation between the global energy expenditure level and the GWP growth rate of Figure 9 are at the root of our business cycle model proposition., Off course, we were largely inspired by the business cycle model proposed by Murphy and Hall (2011a) and represented in Figure 13. However, contrary to these authors, we emphasize the role of energy efficiency gains and we do not need different "functioning modes" for our model to be effective. Indeed, in the representation of Murphy and Hall (2011a) that focuses on the US and its dependency to oil, a distinction is made between two functioning modes: the "Pre-peak era model of economic growth" that would be representative of the pre-peak era (1860-1970) of increasing oil supply, and the "Peak era model of economic growth" that would be representative of the 1970-2020 peak era, i.e. between the time of peak discoveries and the expected peak of oil production. For these authors, when the peak of oil discoveries is not yet attained, business cycles can simply be expressed as a succession of the following three phases: (1) increasing oil demand and GDP induce (2) the prospection for new oil resources that comes with high EROI, which leads to (3) a higher oil supply at decreasing oil prices that allows maintaining (1) economic growth. After the peak of oil discoveries in the 60's, Murphy and Hall (2011a) assert that new deposits were characterized by lower EROI (this is quite in line with the historical estimation of the global EROI of oil advance by Court and Fizaine, 2015). This fact implies to change the business cycle model that is accordingly resumed by the following steps: (1) increasing oil demand and GDP induce (2) the prospection for new oil resources that comes with low EROI, which leads to (3) a higher oil supply with higher oil prices that (4) negatively impact the economy up to recession, which (5) lower the oil demand that consequently implies (6) a decrease of oil prices which finally allows (1) a recovery of economic growth. Referring to Campbell's (2005) undulating plateau for oil production, the "Peak era model" of Murphy and Hall (2011a) implies a higher volatility of economic growth around a flat trend, whereas during the pre-peak era volatility would be lower and around an increasing trend. Logically, these authors propose that their "Peak era model" would still hold during the post peak era (2020 onwards) where oil production would be decreasing in average from one year to another, except that the economic growth would be globally following a decreasing trend too.



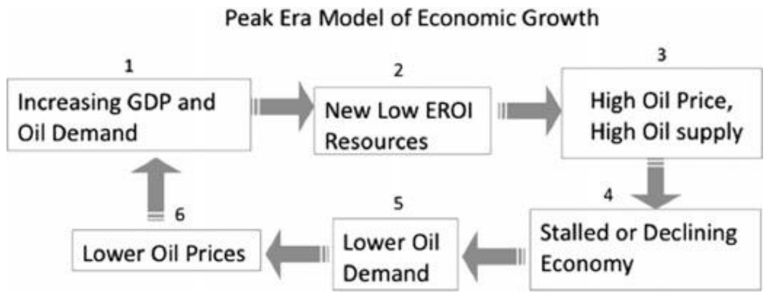


Figure 13. Pre-Peak and Peak era models of economic growth from Murphy and Hall (2011a).

Integrating the crucial role of energy efficiency gains in the model previously presented gives a new feedback analysis allowing a unique model representation represented in Figure 14. Within this business cycle mechanism that we express at the global scale, the GWP growth rate can fluctuates through cycles allowing growth, stagnation and even degrowth phases (major positive feedback loop (A) in Figure 14, i.e. entire business cycle loop). The technological progress stimulation associated with the depletion of high quality resources feeds this fluctuation by influencing the energy intensity of the economy (minor positive feedback loop (B) in Figure 14, i.e. technological sustaining growth loop). The growth state of the economy generates an increasing energy demand that is met by the exploitation of new energy resources that progressively present decreasing marginal returns, which overall induce the EROI to decrease at the societal level. In such context energy prices increases, which imply that the share of GWP allocated to energy expenditures increases and that consequently discretionary investment and consumption decreases. This causes an economic slowdown (or stagnation) that can even turn worse to a degrowth state. In this depressive state, the energy demand would logically decreases, which would translates also into lower fossil energy price, and finally a decrease of the share of the GWP allocated to energy expenditures. At this point, the societal EROI increase is furthermore supported by the energy intensity gains that have been generated through technological progress, which were triggered when energy prices were increasing. Our short and mid-term business cycles mechanism remains valid if one considers a long-term growth, flat or degrowth trend of the economy. This could be adequately represented by different relative speed of rotation of feedback loops (A) and (B) in the Figure 14. If the rotation speed is higher for (B) than for (A), the economy would be in a global increasing trend around which the GWP would fluctuates in short-term business cycles (the pre-peak era of Murphy and Hall, 2011a). If the rotation speed of (A) and (B) are roughly the same, the economy would be on an undulating plateau of cycles around a flat trend (the peak era of Murphy and Hall, 2011a). If the rotation speed is higher for (A) than for (B), the economy would have short-term business cycles around a declining trend (the post-peak era of Murphy and Hall, 2011a). Off course, it is also worth emphasizing that the length of the growth and degrowth phases (left and right side of Figure 14 respectively) can greatly vary from one business cycle to another, depending on different factors that can be intrinsic to a given business cycle (technological diffusion barriers, property rights law, financialization level of the economy, labor organization, constraints on non-energy resources, etc.). This fact is clear when one look at the different switching times identified in section 3.

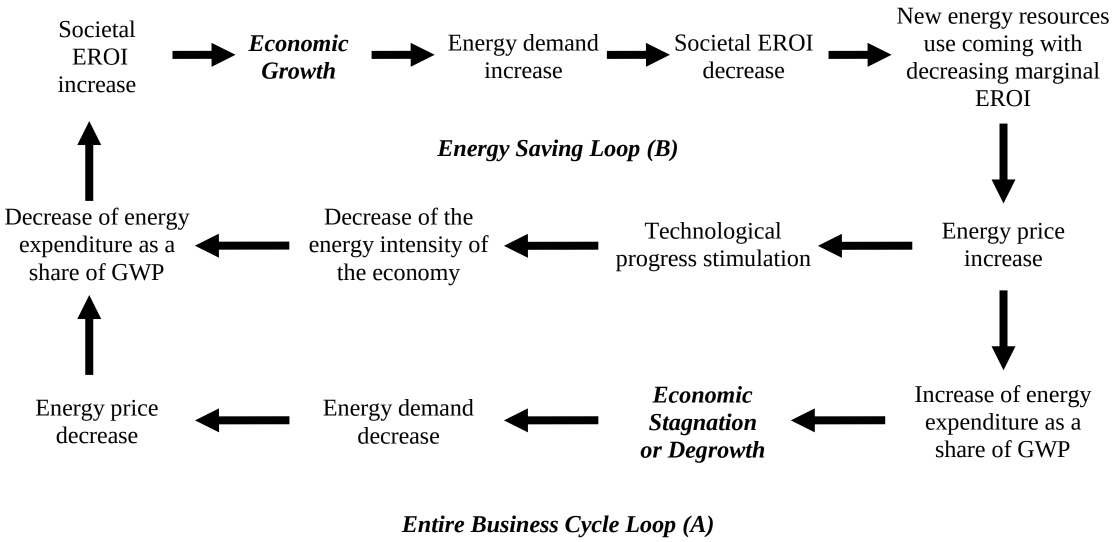


Figure 14. Schematization of the processes underlying the business cycles dynamics through energy depletion channels, price mechanisms and technical progress stimulation

6. Conclusions and policy implications

To our mind, the contribution of the present paper to the scientific literature is four fold. First, our paper has highlighted short and long-term relationships between the global EROI of fossil energy and its weighted average price, and we have seen the central role of the energy intensity of the economy in these relationships. We have observed that all the switching dates of the EROI-energy price short-term relationships (1876, 1929, 1968, 1980, 1998) perfectly correspond to different global economic crisis along the economic history. Second, following previous studies (Murphy and Hall, 2011ab) we have introduced the share of energy expenditures in the GWP as a proxy variable to estimate the role of energy in economic growth. This lead us to find a one way Granger causality running from the level of fossil fuel energy expenditures (as a share of the GWP) to economic growth at 1% of risk (when dummies for the oil shocks are included, or if a three years central moving average of energy expenditures is used instead of dummies). Third, we have shown that beyond an estimated threshold of 15% of energy expenditure in the global economy, economic growth cannot occur. We have been also able to translate this result in both: a maximum tolerable price of fossil energy of 15000 1990$/TJ, and a minimum tolerable global EROI of approximately 7.5:1 beyond which positive growth is not possible for the global economy (at current level of energy intensity). Fourth, based on the previous observations and on the good correlation that we found between the level of the global fossil EROI and the growth rate of the global economy on the 1951-2011 period, we have proposed a model explaining repetitive business cycles patterns. This economic growth fluctuation mechanism is based on the capacity to find new energy resources that accurately respond to energy demand and to take advantage of energy efficiency gains triggered by technological progress stimulation. Yet, further research is needed to determinate more precisely the different factors that influence the time periods of the different phases of the business cycle model we have proposed.

Our results suggest two main facts. First of all, energy plays a crucial role in economic growth, which tends to reinforce the conclusion drawn by the biophysical movement and weakened the mainstream position which sees energy as a common (if not minor) factor of production. If we take the global EROI as a sustainability energy indicator, the fall of the global EROI below its minimum threshold may arise from three different ways. First, this could come from an important decrease of the energy production level ($E_{Out,All\ Energies}$), this is the position supported by the partisan of the peak oil theory. Second, the fall of the EROI could also occur because of an increase of energy investment levels (and associated increases in energy prices) in the different energy sectors due to the decreasing accessibility of energy (typically what is happening when the shares of lower quality fuels such as shale oil and tar sands are increasing in the primary energy supply mix). Finally, the decrease of the global EROI could come from a combination of the two previous possibilities.

Hence, as many before us, we recommend that a coherent economic policy should first of all be based on an energy policy consisting in improving the net energy efficiency of the economy. A "triple dividend" would be associated to this type of measure because it would: increase the global EROI (through a decrease of the energy intensity of capital), decrease the sensitivity of the economy to energy prices volatility, and decreases GHG emissions associated with fossil energy consumption. This recommendation is supported by the importance of crucial role played by the energy efficiency both in the level of energy expenditure spend as a share of GWP and in the determination of the global economy EROI.

After the two oil shocks, economics agents have largely switched toward technologies that consume less energy, leading to a global decrease of the fossil fuel intensity (in comparison with 1950' and 1960' decades). This effort has enabled most of industrialized economies to overcome the impact on economic growth of higher energy prices, while it has also increased the EROI of the global economy. Off course, two important questions remains. First, can new public policies adequately increase the energy efficiency of the economy even in low energy price period? This would be needed in order to prevent the impact of future energy shocks on the economy, which can occur for several reasons: the depletion of cheap and accessible fossil fuels, the adoption of a global CO_2 tax, or the decreasing availability of strategic raw material that are of critical importance for clean energy technologies. Of course, the energy rebound effect would have to be mitigated if we want to maximize the benefits of such policy, which from an historical point of view seems to be rather difficult (Sorrell, 2009). Second, where is the limit to the decrease of the global energy intensity of the economy and when will it be attained?

Acknowledgements

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Appendix: Robustness checks of econometric regressions

Unit root tests (ADF) for the two series "GWP growth rate" and "fossil fuels expenditures"

Variable	Trend and intercept	Constant	None	Result
Ex_GWP	-1.716115	-1.663590	-0.507753	I(1)
Ex_GWP + Dummies	-4.213911***	-3.850120***	-3.048944***	I(0)
Ex_GWP CMA(3)	-3.241376*	-3.231660**	-1.049834	I(0)
log (Ex_GWP) CM(3)	-3.377216*	-3.237069**	-0.593284	I(0)
Growth (GWP)	-6.330259***	-5.862797***	-1.067291	I(0)
D(logGWP)	-6.325245***	-5.857964***	-1.060287	I(0)

* denotes 10% of risk, ** 5% of risk, ***1% of risk. CMA (3): three years central moving average.

For the variable Exp_GDP, two dummies variables have been introduced in the ADF test in order to take into account the effect of the two oil shocks. This can be observed in the residual table of the ADF tests if we do not correct them (first line). The ADF tests indicates that the two series are stationary (I(0)). We can also use a three year central moving average to correct the effect of extreme values mainly due to the oil crises. The tests are also repeated in log form in order to estimate elasticities in the following section.

Normality and homoscedasticity of residuals in the econometric regression of the equation (3):

The table below resumes the main outcomes taken from the econometric estimation of the equation (3). All variables are significant at 5% of risk and most of them at 1% of risk. The Jarque-Bera and White tests indicates that we cannot reject the assumption of normality of residuals and their homoscedasticity. In a similar way, the correlogram of residuals as well as the Durbin Watson statistics point out the absence of residual autocorrelation.

The robustness of our results has been tested by estimating different models:

- Model 1: The growth is regressed on the energy expenditures expressed as a share of GWP plus an intercept.
- Model 2: Similar to model 1 but we have introduced a central moving average of three years for the energy expenditures as a share of GWP.
- Model 3: All variables have been taken in logarithmic forms in order to estimate elasticities.
- Model 4: The US gross capital formation as a share of GDP is integrated in order to introduce a proxy of capital in our estimations as a control variable.
- Model 5: Similar to model 3 augmented by 5 dummies which take into account the impact of several global crisis (the 1973 and 1978 oil shocks, the 1998 Asian crisis, and the recession of 2009).

We have also estimated the relationship between energy expenditures and growth in a VAR model, it does not change the conclusion of the negative impact of the increasing energy expenditures on economic growth.

Method: Least Squares Sample 1951-2011

	Model 1 (dependant variable: Growth)			Model 2 (dependant variable: Growth)			Model 3 (dependant variable: D[log(GWP)]			Model 4'' (dependant variable: Growth]		
Variables	**Coeff.**	**Sd. Error**	**Prob.**	**Coeff.**	**Sd. Error**	**Prob.**	**Coeff.**	**Sd. Error**	**Prob.**	**Coeff.**	**Sd. Error**	**Prob.**
Ex_GWP	**-0.326641*** **	0.088570	0.0005	-	-	-	-	-	-	-	-	-
Ex_GWP CMA(3)	-	-	-	**-0.326241*** **	0.092334	0.0008	-	-	-	**-0.362002*** **	0.107285	0.0016
Log(Ex_GWP) CM(3)	-	-	-	-	-	-	**-0.010505*** **	0.000452	0.0000	-	-	-
C	**0.048926*** **	0.003244	0.0000	**0.048737*** **	0.003164	0.0000	-	-	-	**0.048315*** **	0.005087	0.0000
Capital (US)										**0.836596*** **	0.156028	0.0000
Ar(3)										**0.398259*** **	0.121088	0.0020
R-squared	0.131314	-	-	0.124252	-	-	0.137394	-	-	0.552544	-	-
Adjusted R-squared	0.116591	-	-	0.108888	-	-	0.137394	-	-	0.520583	-	-
Schwarz criterion	-5.629834	-	-	-5.631310	-	-	-5.785231	-	-	-6.094382	-	-
F-statistic	8.918699	-	0.004106	8.087181	-	0.006179	-	-		17.28803	-	0.000000
Durbinwatson	1.626623	-	-	1.581285	-	-	1.608770	-	-	1.826620	-	-
Q-stat (lag 1)	1.8133	-	0.178	2.2373	-	0.135	1.8635	-	0.172	-	-	-
Q-stat (lag10)	7.4814	-	0.679	7.4224	-	0.685	4.9393	-	0.895	4.6713	-	0.862
Heteroskedasticity Test: White	0.463027	-	0.6317	1.547202	-	0.2218	0.660035	-	0.4199	1.157995	-	0.3502
Jarque-Beranormality	5.395471	-	0.0677358	3.5989	-	0.165	3.228497	-	0.199	4.9620096	-	0.084
Ex_GDP max (min-max) at 5%	0.085	0.1498	0.215	0.08	0.1494	0.219	-	-	-	-	-	-
Energy price max (EI = 9.95MJ/$1990)	8500	14980	21500	8 040	15 015	22 010	-	-	-	-	-	-
EROI min (MROI = 1.15)	13.38	7.59	5.29	14.22	7.61	5.19	-	-	-	-	-	-

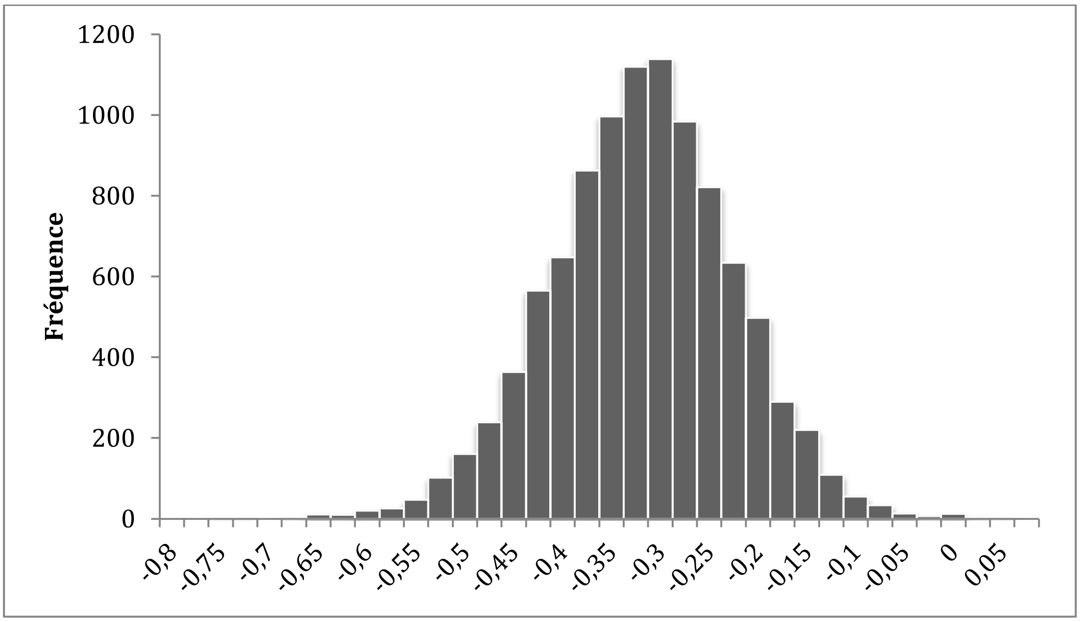
* denotes 10% of risk, ** 5% of risk, ***1% of risk. Robust standard errors (White heteroscedasticity-consistent standard errors & covariance). The capital variable has been introduced in the equation without its trend ensuring that the variable is I[0]. The model 4 is estimated only on the 1965-2010 period due to unavailability of US capital data for the 1951-1964 time period.

	Model 5 (dependant variable: Growth)		
Variables	Coeff.	Sd. Error	Prob.
Ex_GWP CMA(3)	**-0.384693*** **	0.130369	0.0049
C	**0.052032*** **	0.004331	0.0000
Ar(4)	**0.371668*** **	3.082839	0.0034
Dum1974	**-0.021082*** **	-3.184397	0.0026
Dum1979	**0.017298*** **	4.049961	0.0002
Dum1991	**-0.025305*** **	-14.80088	0.0000
Dum1998	**-0.021259*** **	-7.636938	0.0000
Dum2009	**-0.047977*** **	-24.05287	0.0000
R-squared	0.493425	-	-
Adjusted R-squared	0.417977	-	-
Schwarz criterion	-5.726795	-	-
F-statistic	6.539984	-	0.000021
Durbinwatson	1.590591	-	-
Q-stat (lag 1)	-	-	-
Q-stat (lag10)	3.9703	-	0.9130
Heteroskedasticity Test: White	1.037365	-	0.4389
Jarque-Beranormality	0.081462	-	0.9600
Ex_GDP max (min-max) at 5%	0.061	0.135	0.21
Energy price max (EI = 9.95MJ/$1990)	6130	13570	21100
EROI min (MROI = 1.15)	17.16	7.75	4.98

Results for the regression of equation (3) with 10 000 bootstrapping replications

The result of the regression of the equation (3) was also confirmed with 10 000 bootstrap replications in order to check both the value of coefficients and the standard error associated with these coefficients.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.0489***	0.0032	14.85	0.0001
EX_GDP	-0.3266***	0.0915	-3.49	0.0009



Distribution of values for the coefficientof regression of energy expenditures on GWP with 10 000 bootstraps replications.

Cointegration tests

The two series exhibits also a cointegration relationship as shown by the test of Engle-Granger and the test of Johansen.

Series: EX_GDP GROWTH
Sample: 1951 2011
Included observations: 60
Null hypothesis: Series are not cointegrated
Cointegrating equation deterministics: C
Automatic lags specification based on Schwarz criterion (maxlag=10)

Dependent	tau-statistic	Prob.	z-statistic	Prob.
EX_GWP	-6.565070	0.2853	-11.68203	0.2400
GROWTH	-6.565070***	0.0000	-49.85088***	0.0000

* denotes 10% of risk, ** 5% of risk, ***1% of risk.

Date: 09/11/15 Time: 13:37
Sample (adjusted): 1953 2011
Included observations: 59 after adjustments
Trend assumption: Linear deterministic trend
Series: GR EX_GWP

Lags interval (in first differences): 1 to 1

Unrestricted Cointegration Rank Test (Trace)

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.272502	21.94089	15.49471	0.0046
At most 1	0.052317	3.170399	3.841466	0.0750

Trace test indicates 1 cointegrating eqn(s) at the 0.05 level
* denotes rejection of the hypothesis at the 0.05 level
**MacKinnon-Haug-Michelis (1999) p-values

Unrestricted Cointegration Rank Test (Maximum Eigenvalue)

Hypothesized No. of CE(s)	Eigen value	Max-Eigen Statistic	0.05 Critical Value	Prob.**
None *	0.272502	18.77049	14.26460	0.0091
At most 1	0.052317	3.170399	3.841466	0.0750

Max-eigenvalue test indicates 1 cointegrating eqn(s) at the 0.05 level
* denotes rejection of the hypothesis at the 0.05 level
**MacKinnon-Haug-Michelis (1999) p-values

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