Chaire Economie du Climat
Université Paris-Dauphine
CDC Climat

WORKING PAPER
n° 2015-10 • Octobre 2015

KEYWORDS
.
EROI
.
Fossil energy prices
.
Theoretical EROI function
.

ESTIMATIONS OF VERY LONG-TERM TIME SERIES OF GLOBAL ENERGY-RETURN-ON-INVESTMENT (EROI) FOR COAL, OIL, AND GAS PRODUCTIONS

Victor COURT[1,2,3] and Florian FIZAINE[4]

In the present paper we propose a methodology to assess the global EROI of coal, oil, and gas, from the beginning of their reported production (respectively 1800, 1860 and 1890) to 2011. We first estimate on the same time periods the global time series of the energy prices of these different fossil fuels, the monetary return on investment of the energy sector, and the total energy intensity of the economy. These preliminary results allow us to estimate the historical global EROI of coal, oil and gas productions, and the historical EROI of the global primary fossil energy sector. We find that the maximum EROI of global oil and gas productions have respectively reached the values of 73:1 in 1931 and 200:1 in 1945, which is in line with previous studies that had hypothesized such results. Furthermore, we suggest that the EROI of global coal production has not yet reached its maximum value and that marginal gains are still to be expected in this sector thanks to coming technological improvement. We then present a new theoretical dynamic expression of the EROI of a given energy resource as a function of its cumulated production based on the original work of Dale et al. (2011). Modifications of the original model were needed in order to be able to perform calibrations on each of our price-based historical estimates of coal, oil, and gas global EROI. The calibrations of the theoretical models confirm that the maximum EROI of global oil and gas productions have both already been reached in the 1940' around 60±15 and180±20 respectively. We then use the theoretical EROI models in a prospective exercise and found that they give very consistent results for oil and gas since their maximum EROI is already passed. Regarding coal, we obtain more different outputs. Even if it is impossible to give a really precise estimation, we think it can be fairly postulated that the maximum coal EROI will occur between 2020 and 2045, around a value of 110(±20).

JEL codes: N7, Q3, Q4, Q57.

Chaire Economie du Climat
Palais Brongniart, 4ième étage
28 place de la bourse
75002 PARIS

1. EconomiX, UMR 7235, Université Paris Ouest Nanterre - La Défense, 200 av. de la République, 92001 Nanterre, France. victor.court@chaireeconomieduclimat.org

2. IFP Énergies Nouvelles, IFP School, 1-4 av. du Bois Préau, 92852 Rueil-Malmaison, France.

3. Chaire Economie du Climat, Palais Brongniart, 28 place de la Bourse, 75002 Paris, France.

4. Réseaux, Innovation, Territoires et Mondialisation (RITM), Univ. Paris-Sud, Université Paris-Saclay, 54, Boulevard Desgranges, 92330 Sceaux, France. florian.fizaine@gmail.com

1. Introduction

The view of the human society as a biophysical system has been expressed in the pioneering works of Odum (1971, 1973), Georgescu-Roegen (1971, 1979), Cleveland et al. (1984) and more recently by 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). From a more practical point of view, this stream of thought has been represented by the energy science literature (input/output analysis, energy and mass flows accounting, etc.) that started at the same time. In particular, the Energy-Return-On-(Energy)-Investment (EROI or EROEI) has attracted many attention since any organism or system needs to procure at least as much energy as it consumes in order to pursue its existence. The EROI is the ratio of the quantity of energy delivered by a given process to the quantity of energy consumed in this same process. Hence, the EROI is a measure of the accessibility of a resource, meaning that the higher the EROI the greater the amount of net energy delivered to society in order to support economic growth (Hall et al., 2014). For the partisans of biophysical economics, it makes no doubt that the development of industrial societies has been largely dependent on fossil fuels, and in particular on their high EROI and consequent capacity to deliver large amounts of net energy to society.

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[1]. 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 geologically rare metals incorporated in their construction. Hence, for now performing an energy transition towards renewable technologies seems to necessarily imply a 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

[1] 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.

fossil energy supply could potentially 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 (Hall and Day, 2009; Hall et al., 2009; Murphy and Hall, 2010, 2011a, 2011b; Lambert et al., 2014); but it is worth emphasizing that the EROIs of the different fossil energy types used in the economy have never been formally estimated from their respective starting time of production to present days. In the current paper, we propose a methodology to achieve such a goal. While some of the results clearly comfort educated guesses about global oil and gas (namely, that their maximum EROI has already been reached in the past); results regarding global coal EROI are quite innovative and counterintuitive. We are going to see that our methodology allows an estimation of the global EROI of coal, oil, and gas, up to the beginning of their reported production (respectively 1800, 1860, and 1890). In order to do that, we have had first to recover different coherent time-series for the same time periods, concerning: the energy prices of the different fossil energy types, the global primary fossil energy mix, the monetary return on investment (MROI) of the energy sector, and the energy intensity of capital expenditure in the primary fossil energy sector. These data estimations allowed us to compute an average price of fossil energy weighted by the quantities of produced fossil energy from 1800 to 2011, and to subsequently build time-series estimations of the global EROI of the diverse fossil energy resources (coal, oil and gas) and of the global primary fossil energy system over the same time period. The methodology employed to compute the time-series of energy prices and EROI of the different fossil energy resources and finally estimate the EROI of the global primary fossil energy system are presented in section 2. The results of these estimations are presented and commented in section 3. In section 4 we propose a new theoretical dynamic expression of the EROI of a given energy resource as a function of its cumulated production, based on the original work of Dale et al. (2011). Confrontations of this theoretical model with our historical price-based estimates of the EROI of global coal, oil, and gas productions are then performed. Finally, in section 5 we conclude and propose some research perspectives that would be worth investigating as an extension of the present work.

2. Methodology and data

2.1 Equations to estimate the global EROI of primary fossil energy

Our methodology to estimate the EROI of global primary fossil energy systems is inspired by the work of King and Hall (2011). We propose for this methodology three variants labeled A, B, and C. We use the index *i* to refer to these alternatives, so $i \in (A, B, C)$. As expressed by the relation (1), the $EROI_j$ (unitless) of the fossil energy sector $j \in (Coal, Oil, Gas, All\ Fossil\ Fuels)$ can be simply expressed as the ratio of the energy produced $E_{out,j}$ (expressed in exajoule, or EJ) by the energy sector j divided by the energy $E_{in,j}$ (EJ) invested in this same energy sector.

$$EROI_j = \frac{E_{out,j}}{E_{in,j}} \tag{1}$$

Estimating the j different $E_{out,j}$ is rather simple since databases for coal, oil and gas historical productions are quiet reliable. On the other hand, estimating the quantities of energy $E_{in,j}$

invested in each energy sector is rather difficult and represents the very source of complications when one tries to compute an EROI. Regarding the larger global economy, it can be proposed that the energy $E_{in,j}$ (EJ) invested in the global energy system *j* corresponds to the quantity of money $M_{in,j}$ (expressed in million dollars, or M$) invested in this sector multiplied by the energy intensity EI_j (EJ/M$) of the capital installed and run in the energy sector *j* (i.e. the quantity of energy spend in the economic system to generate a unitary dollar spent in capital installation and energy consumption in the energy sector *j*).

$$EROI_j = \frac{E_{out,j}}{M_{in,j} * EI_j} \tag{2}$$

Of course the problem now lies in the estimation of the quantity of money $M_{in,j}$ invested in the global energy sector for which very few data exist. Thus, we will assume that the unitary price P_j (M$/EJ) of a given energy type divided by the Monetary Return on Investment or $MROI_j$ (unitless) of the energy sector *j* is a proxy for the levelized cost of this same energy. This will allow us to estimate the total money $M_{in,j}$ invested in a given energy sector *j* by multiplying the quantity of energy produced $E_{out,j}$ by this sector with the proxy levelized cost of this same energy:

$$M_{in,j} = \frac{P_j}{MROI_j} * E_{out,j}. \tag{3}$$

By injecting (3) into (2), we obtain that the $EROI_j$ of the energy sector *j* at global level will be computed each year as follow:

$$EROI_j = \frac{MROI_j}{P_j * EI_j}. \tag{4}$$

Due to data availability, we have to make two further assumptions. First, the $MROI_j$ of all *j* energy sectors are the same but we found three $i \in (A, B, C)$ possibilities to estimate this MROI. Second, the energy intensities EI_j of all *j* energy sectors are the same and correspond to the energy intensity *EI* of the global economy. *EI* can easily be calculated with:

$$EI = \frac{\sum_k E_{out,k}}{GWP}, \qquad k \in (Coal, Oil, Gas, Nuclear, All\ Renewables) \tag{5}$$

where GWP (M$) is the Gross World Production. We remark that in order to calculate the variable *EI*, we have to include the other quantities of energy productions coming from nuclear and renewable energy forms (wind, solar, geothermic, ocean, biofuels, wastes, etc.). It follows from these assumptions that (4) becomes (6).

$$EROI_{i,j} = \frac{MROI_i}{P_j \times EI} \tag{6}$$

Then, estimating the global $EROI_{i,fossil}$ of the total primary fossil energy sector is straightforward.

$$EROI_{i,All\ Fossil\ Fuels} = \frac{MROI_i}{P_{All\ Fossil\ Fuels} \times EI} \quad (7)$$

Where $P_{All\ Fossil\ Fuels}$ (M$/EJ) represents the average price of fossil energy weighted by the different quantities of produced fossil energies defined by:

$$P_{All\ Fossil\ Fuels} = \sum_j P_j * \frac{E_{out,j}}{\sum_j E_{out,j}}. \quad (8)$$

The methodology presented above requires having consistent time series for: energy quantities (EJ), energy prices (M$/EJ), GWP (M$), and the three estimations $i \in (A, B, C)$ of the $MROI_i$ (unitless).

2.2 Data collection and harmonization

The first data collection concerns the price of the different energy types. We have used several sources summarized in Table 1 for these prices and made the accurate conversion so that all prices are expressed in 1990$/TJ (here terajoule is used instead of exajoule for graphical convenience, see Figure 6 and 7). Unfortunately, as exposed in Table 1 most of existing long-term time series of energy prices only concern American markets. We will nevertheless use these data by considering that international markets are competitive and that large spread between energy prices cannot last for long due to arbitrage opportunities. Harmonizing the different energy prices to express them in constant 1990$ per energy unit has required the use of a Consumer Price Index found in Officer and Williamson (2013) and different energy conversion factors such as: the energy content of one barrel of oil (6.1E-03 TJ), the energy content of one tonne of coal (29.5E-03 TJ), the energy content of one thousand cubic feet of gas (1.06E-03 TJ).

Table 1. Sources and original unit of the different energy prices used in this study.

Energy type	Time frame	Source	Original unit
Coal	1800-2011	US Bureau of the Census (1975), EIA (2012a)	Nominal $/tonne[2]
Oil	1860-2011	BP Statistical Review (2014)	2009$/barrel
Gas	1890-2011	US Bureau of the Census (1975), Manthy (1978), EIA (2012b)	Nominal $/thousand cubic feet

In order to compute the EROI estimations, we have also used the different data presented in the following Figure 1, 2, 3 and 4. Energy production values have been retrieved through the online data portal of The Shift Project (2014) which is built on the original work of Etemad and Luciani (1991) for the 1900-1980 time period and EIA (2014) for 1981-2011. Prior to 1900, we have completed the different fossil fuels time series with the original work of Etemad and Luciani (1991) and filled the gaps by linear interpolation (Figure 1). The work of Fernandes et al. (2007) and Smil (2010) were used to retrieve historical global consumption of biomass energy (wood and crop residues that still represents 50% of the total

[2] We refer here to the International System of Units, 1 tonne represents 1000 kilograms. The original data were expressed in different mass units (1 short ton =0.91 tonne, 1 long ton=1.02 tonne, and 1 pound= $3{,}73\times10^{-4}$ tonne) so adequate conversions have been performed.

renewable energy production nowadays, whereas hydro accounts for 42% and new renewables technologies such as wind power, solar PV and geothermal take the remaining 8%). Concerning the Gross World production (GWP), expressed in million 1990 international Geary-Khamis dollar[3], we used the data of Maddison (2007) from 1800 to 1950 and GWP per capita of The Maddison Project (2013) multiplied by the United Nations (2015) estimates of global population from 1950 to 2011 (Figure 2). Regarding the estimation of the Monetary Return On Investment (MROI) in the energy sector, since we have tested three different sources we will consequently generate three variants (A, B, and C) of the methodology previously presented in section 2: (A) the MROI is equal to the USA long-term interest rate provided by Officer (2015) from 1800 to 2011 and majored by a 10% risk premium[4] (Figure 3); (B) the MROI is based on a reconstructed AMEX Oil Index[5] based on a relation estimated between the AMEX Oil Index data of Reuters (2015) for the period 1984-2009 and the NYSE Index data on this same period, with prior NYSE Index retrieved from Goetzmann et al. (2000) for the 1815-1924 period, Ibbotson and Sinquefield (1976) for the 1925-1974 period, and NYSE (2015) the 1975-2011 period (Figure 4); (C) the MROI is considered constant and equal to 1.1 (i.e. the energy sector margin is 10%). We summarize in Table 2 the different methodology employed to estimate the MROI supposed equal in all fossil energy sectors and reported in Figure 5. These three variant MROI estimations logically induce three EROI estimations for each fossil fuel.

Table 2. Synthetic description of the three possible methodology variant A, B, and C employed in this study to estimate the MROI supposed common to all fossil energy sector.

Variant name	Main assumptions in methodology
A	$\boldsymbol{MROI_A = ((USA.LTIR + 10)/100) + 1}$.
B	$\boldsymbol{MROI_B = 1 + AMEX\ Oil\ Index_{estimated}}$.
C	$\boldsymbol{MROI_c}$ **is constant and equals 1.1**

Regarding the variant B, the variable $AMEX\ Oil_{estimated}$ is computed following the relation (9), which parameters values were obtained through a regression on the AMEX data of Reuters (2015) on the period 1984-2009:

$$AMEX\ Oil\ Index_{estimated} = 0.05466 + 0.65233 * NYSE_{data} \quad (9)$$

[3] The 1990 International Geary–Khamis dollar (Int. G-K.1990$), more commonly known as the international dollar, is a standardized and fictive unit of currency that has the same purchasing power parity that the U.S. dollar had in the United States in 1990.
[4] This 10% risk premium is in line with the risk premium estimated by Damodaran (2015) for the oil and gas sector.
[5] The NYSE Arca Oil Index, previously AMEX Oil Index, ticker symbol XOI, is a price-weighted index of the leading companies involved in the exploration, production, and development of petroleum. It measures the performance of the oil industry through changes in the sum of the prices of component stocks. The index was developed with a base level of 125 as of August 27th, 1984.

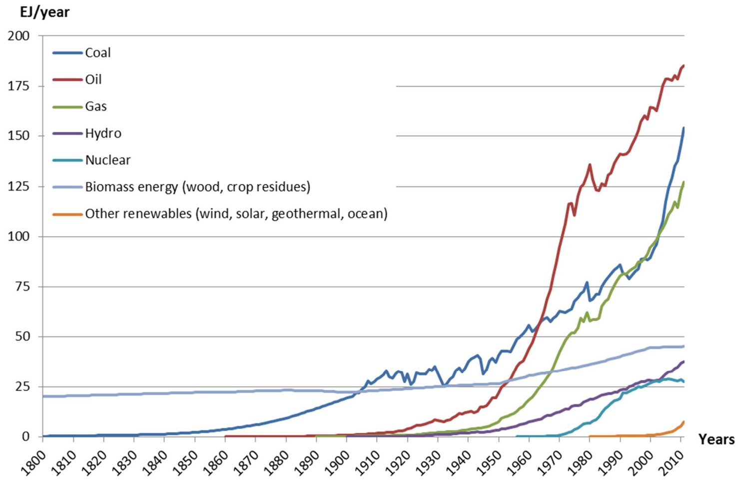

Figure 1. Primary energy productions (EJ/year) used to compute the energy intensity of the global economy in the three methodology variants A, B, and C. Data sources: Etemad and Luciani (1991), Fernandes et al. (2007), Smil (2010), The Shift Project (2014).

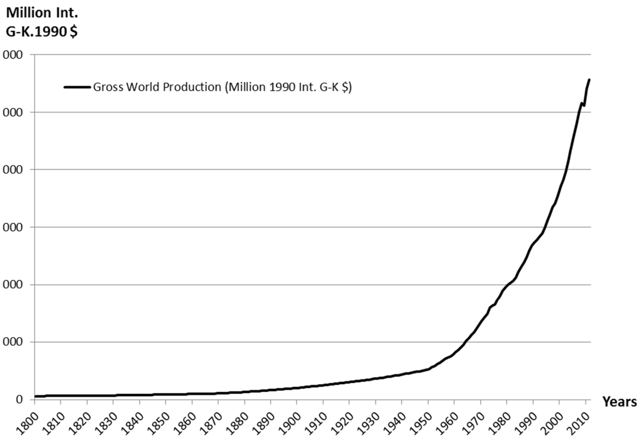

Figure 2. Gross World Production (GWP) in million 1990 international Geary–Khamis dollars used to compute the energy intensity of the global economy in the three methodology variants A, B, and C. Data sources: Maddison (2007), The Maddison Project (2013), United Nations (2015).

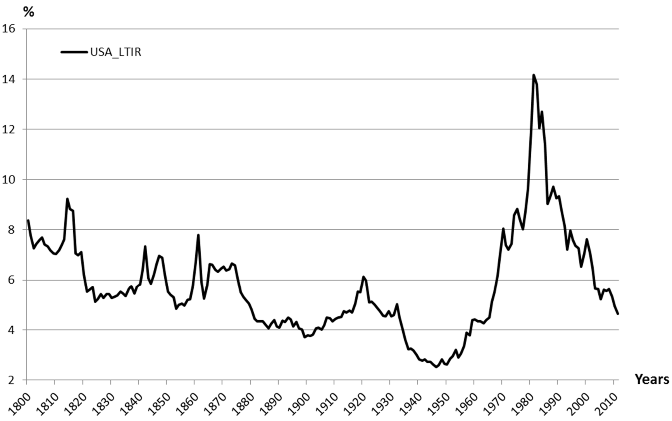

Figure 3. USA long term interest rate (USA_LTIR) used in methodology A. Data source: Officer (2015).

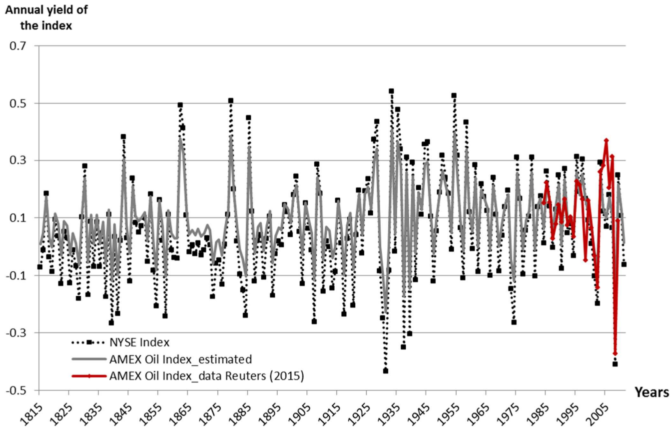

Figure 4. Reconstructed AMEX Oil Index annual yield (grey line) used in methodology B from 1815 to 2011 through a calibration on the NYSE Index (black dashed line) retrieved from Goetzman et al. (2000) for the 1815-1924 period, Ibbotson and Sinquefield (1976) for the 1925-1974 period, and NYSE (2015) for 1975-2011. The original AMEX Oil Index data of Reuters (2015) for the period 1984-2009 is shown in red.

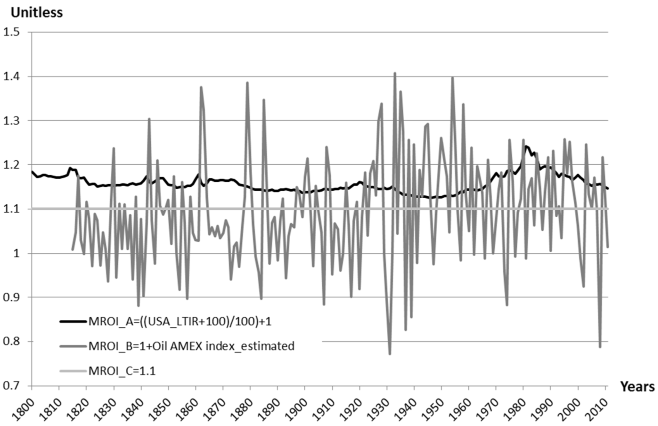

Figure 5. Comparison of the three estimation variant for the MROI supposed equal in all fossil fuels sectors.

3. Results

Since it is impossible to find long-term time series of fossil energy prices for coal, oil, and gas expressed in constant dollars per similar energy unit in a unique study, the ones we have produced in the present paper constitute an achievement that is worth presenting as a result. Then, we will present our various estimations (A, B, and C) of the global EROI of the different fossil energy types and of the total primary fossil energy system.

3.1 Time series of energy prices in 1990$/TJ

The different time series of fossil energy prices that we have produced are presented in Figure 6. The associated estimation of the average price of fossil energy weighted by the quantities of produced fossil energies that we have computed from 1800 to 2011 is shown in Figure 7.

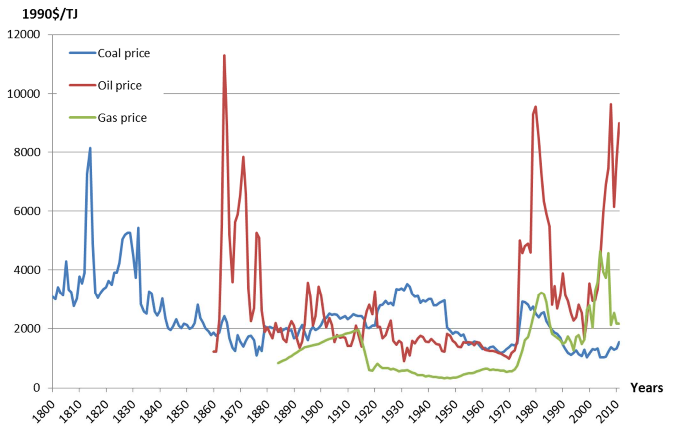

Figure 6. Estimations of global energy prices for coal (1800-2011), oil (1860-2011) and gas (1890-2011) in 1990$/TJ.

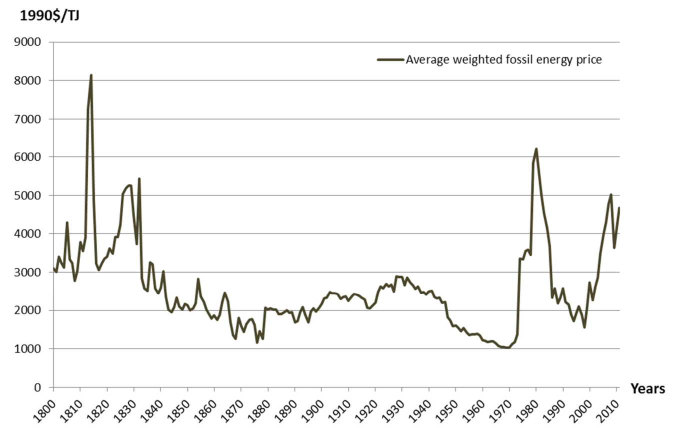

Figure 7. Estimation of the average price of fossil energy weighted by the quantities of produced fossil energies from 1800 to 2011 in 1990$/TJ.

Furthermore, we present in Figure 8 the energy intensity of the global economy over time (expressed here for convenience in MJ per Int. G-K.1900$) that we have computed in this study, as it is rather different from the one seen in some studies (e.g. Rühl et al., 2012) where traditional biomass energy (wood, crop residues) consumption is not accounted for.

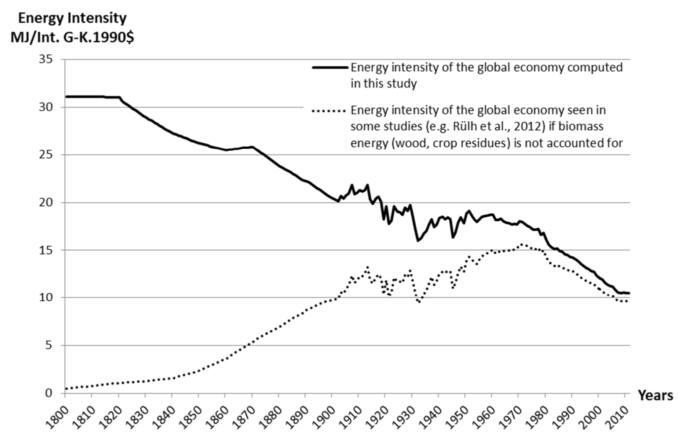

Figure 8. Comparison of the energy intensity of the global economy over time (MJ/Int. G-K.1990$) when traditional biomass energy (wood, crop residues) is accounted for or not.

3.2 Historical time series of global EROI

Since we have three methodology variants (A, B, and C) to estimate the global EROI of the three fossil fuels (coal, oil, and gas), we will: (i) compare the estimations of the three methodologies for each fossil energy type and choose the best methodology among the three alternatives; (ii) compare the estimations of the global EROI of the different fossil energies and of the total primary fossil energy system with the methodology selected as the best one.

<u>(i) Comparison of the three methodology variants for each fossil energy type and choice of the best methodology</u>

Figure 8 presents our estimations of the global EROI of coal, oil, gas, and of the primary fossil energy system with the three possible methodologies. It can easily be seen that the three methodologies deliver very consistent results. Indeed, when looking at a particular energy type it is difficult to make a distinction between the different EROI estimations because methodological alternatives do not generates large enough output differences. However, since there is a slightly higher volatility with values from methodology B (that moreover cannot starts in 1800 because of the impossibility to estimate the $MROI_B$ before 1815) and considering that methodology C is the more basic in its assumptions, we consider that among the three possible alternatives, the variant A is the best one. Hence, for the sake of clarity and convenience, we will only consider the variant A in the following of the paper.

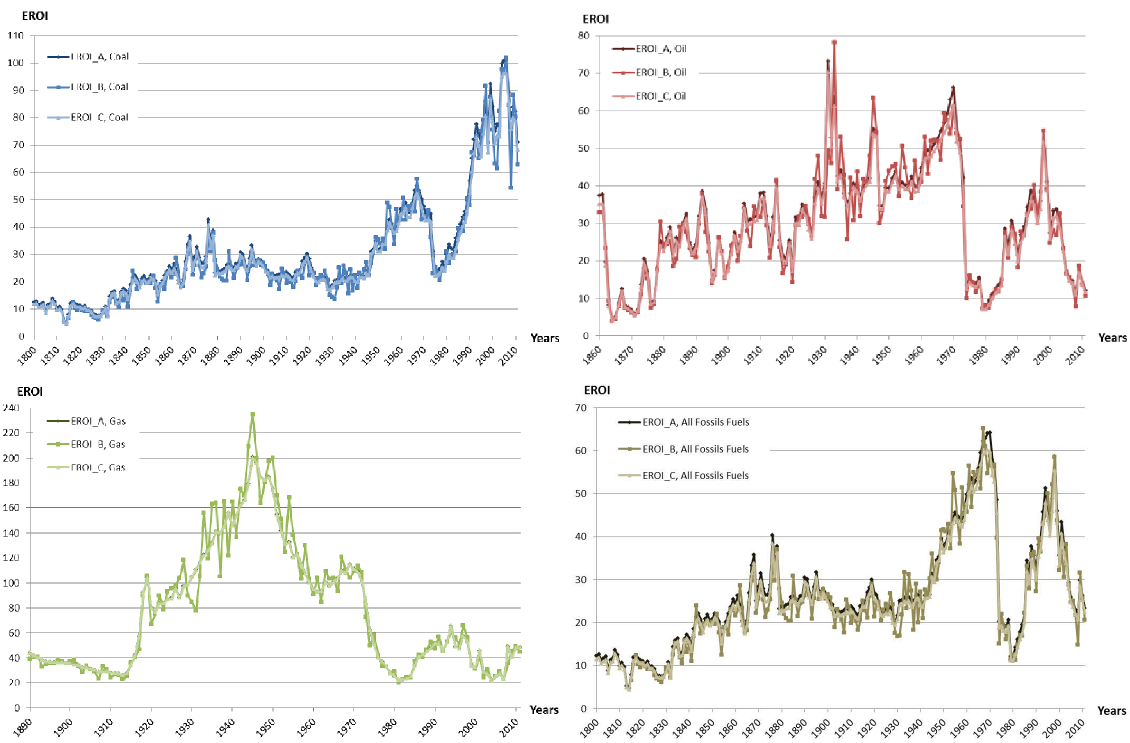

Figure 8. Comparison of the three methodologies A, B, and C, for estimating the global EROI of coal, oil, gas and of the total primary fossil energy system.

(ii) Comparison of the estimations of the global EROI of the different fossil energies and of the total primary fossil energy system with the methodology A

Figure 9 presents the estimations of the global EROI of coal, oil, gas, and of the total primary fossil energy system according to the price-based methodology A.

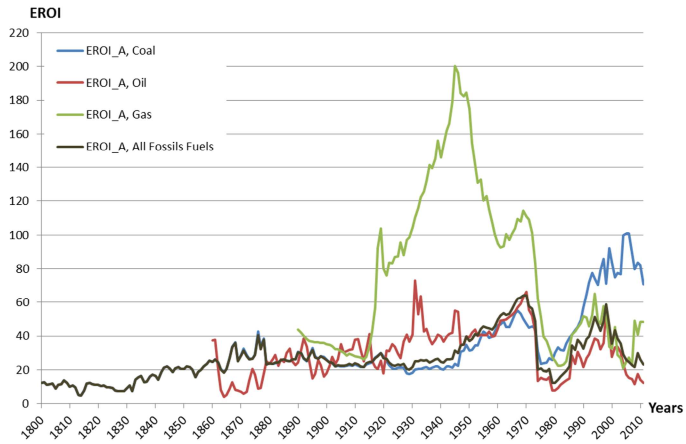

Figure 9. Global EROI of coal, oil, gas, and of the total primary fossil energy system estimated with the price-based methodology A.

It is interesting to see that according to our estimations, and contrary to what common sense would suggest, the global EROI of the three fossil fuels (coal, oil, and gas) were not maximum at the early years of their respective (reported) productions. Yet, these maximum EROI seems to have already been achieved in the past for the global oil (red line) and gas (green line) productions, with the respective values of 73:1 for oil in 1931 and 200:1 in 1945. Regarding global coal production (blue line), its EROI seems to have even broadly steadily increased from 1800 to present, indicating that maximum EROI has not yet been attained for this energy resource. Furthermore, we can observe in Figure 9 that broadly the global EROI of the total primary fossil energy system has followed the global EROI of coal from 1800 to 1955 and then the one of oil from 1965 to 2011. From 1955 to 1965, the situation is more difficult to analyze since the EROI of coal and oil are hardly discernable. This is quite logical in the perspective of the historical energy productions data reported in Figure 1 where it can be found that 1964 is the year at which global oil production becomes for the first time more important than global coal production.

In order to better analyze the course of these EROI dynamics, we will compare in section 4 these price-based estimations to theoretical dynamic models of the EROI as a function of cumulated production. Before this, it is worth identifying some biases in the price-based methodology that we have proposed to estimate historical EROI, and compare our results with existing studies.

3.3 Biases in the price-based approach

As can been seen in equation (7), the estimation of the global $EROI_{A,All\ Fossil\ Fuels}$ of the total primary fossil energy sector is sensitive to the uncertainty surrounding the value of its three arguments: the average price of fossil energy $P_{All\ Fossil\ Fuels}$; the $MROI_A$, and the energy intensity EI of the global economy. The different fossil energy prices that constitute the average price of fossil energy integrate investment in energy sectors but also different kinds of rents, in particular during temporary exercise of market power, that are not taken into account in the $MROI_A$ proxy. This implies that, on particular points that we cannot identify, we might have overestimated the expenditures level in a given energy sector and consequently underestimated its associated EROI. But considering that the fossil energy prices that we have used come from historical data that we consider to be robust, we think that our results are mostly subjected to the uncertainties surrounding the variables $MROI$ and EI. In fact, since we have shown in Figure 8 a consistency of our results to the three estimation variants (A, B, and C) of the MROI, we have in a way already tested the sensitivity of our EROI estimates to the uncertainty surrounding the MROI. But we have to acknowledge that we have no clue on the magnitude of approximation to the real MROI of the different fossil energy sectors through the proxy $MROI_A$. In addition, it is very likely that the different expenditures of the global fossil sector present overall a higher energy intensity than the expenditures of the global economy. Thus, by taking the energy intensity of the global economy as a proxy for the energy intensity of the expenditures of the fossil energy sector, we have logically overestimated the different EROI that we have calculated through our three methodology variants.

Using (7), we can compute for a given year (we choose the last one, 2011) some isocurves of the EROI, which represent the same level of EROI for different combination of $MROI$ (unitless) and energy intensity EI (MJ/1990$) while the level of the fossil energy price is considered as fixed (Figure 10).

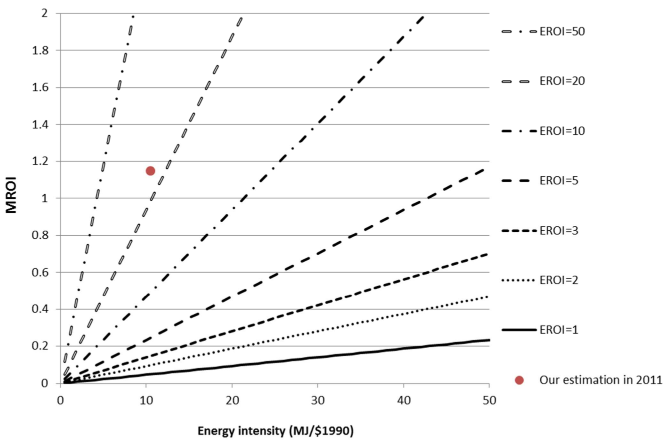

Figure 10. Sensitivity of the global EROI of the total primary fossil energy sector of the year 2011 to the energy intensity (abscissa axis) and to the MROI (ordinate axis).

3.4 Robustness assessment by comparison with existing studies

To check the robustness of our price-based estimations and the impact of the potential biases suggested above, we use the work of Gagnon et al. (2009) in which an estimation of the global EROI of the combined oil and gas production is done from 1992 to 2006. Hence, using the methodology A again, we built an estimation of the global EROI of the joint oil and gas production and compared it to the one of Gagnon et al. (2009) (Figure 11). Overall, our estimation of the global EROI of oil and gas follows the same trend as the one of Gagnon et al. (2009): an increase between 1992 and 1999 followed by a decreasing phase up to 2006. Our estimation is globally higher and much more volatile than the one of Gagnon et al. (2009). This difference might come from the different biases enounced in the previous section but we cannot say which of these biases is dominating. To estimate the importance of the overall potential bias, we multiplied the denominator of the equation (7) by a parameter that we calibrated in order to minimize the sum of squared errors deriving from the difference between our estimation of the global EROI of oil and gas and the one of Gagnon et al. (2009)

on the period 1992-2006. We found that in average our EROI overestimate the one of Gagnon et al. (2009) by a 1.2 factor (i.e. by 20%).

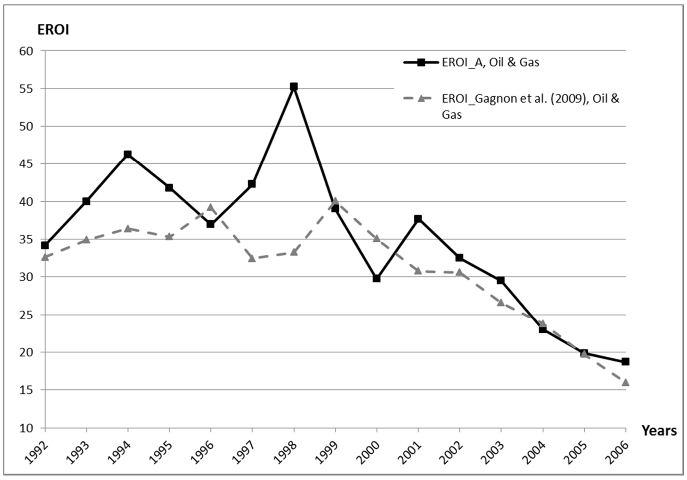

Figure 11. Comparison of the global EROI of oil and gas from methodology A with the one of Gagnon et al. (2009) between 1992 and 2006.

It is also worth noting that regarding the EROI of coal, values around 80:1 presented by our results in the last decade are perfectly in line with the estimation of the American coal EROI of Cleveland (2005).

4. Discussion on the concordance of our historical global EROI estimates and a new theoretical dynamic expression of the EROI as a function of cumulated production

Dale et al. (2011) have proposed a dynamic expression of the EROI of a given energy resource as a function of its cumulated production. Despite the use of such functional expression of the EROI in a broader theoretical model called GEMBA (Dale et al., 2012), the accuracy of this theoretical model on historical EROI estimates of fossil fuels has never been tested. Now that we have provided these estimations for coal, oil, and gas from their respective beginnings of production to present time, such comparison with the theoretical model of Dale et al. (2011) is now feasible. Yet, we found that the theoretical model of Dale et al. (2011) needs to be slightly modified in order to correct two drawbacks.

4.1 A new theoretical dynamic model of the EROI as a function of cumulated production

Theoretical considerations

Like Dale et al. (2011), we assume that the $EROI_k$ of a given energy resource k (either nonrenewable or renewable) depends on a scaling factor ε_k, which represents the maximum potential EROI value (never formally attained); and on a function $F(\rho_k)$ depending on the exploited resource ratio $0 \leq \rho_k \leq 1$, also known as the normalized cumulated production, i.e. the cumulated production P_k normalized to the size of the Ultimately Recoverable Resource[6]

[6] According to BP (2015): the "URR is an estimate of the total amount of a given resource that will ever be recovered and produced. It is a subjective estimate in the face of only partial information. Whilst some consider URR to be fixed by geology and the laws of physics, in practice estimates of URR continue to be increased as knowledge grows, technology advances and economics change. The ultimately recoverable resource is typically broken down into three main categories: cumulative

URR_k defined as the total resource that may be recovered at positive net energy yield, i.e. at EROI greater of equal to unity.

$$\rho_k = \frac{P_k}{URR_k}. \tag{10}$$

As shown in relation (11), $F(\rho_k)$ is the product of two functions, $G(\rho_k)$ and $H(\rho_k)$. $G(\rho_k)$ is a technological component that increases energy returns as a function of ρ_k, which here serves as a proxy measure of experience, i.e. technological learning. $H(\rho_k)$ is a physical component that diminishes energy returns because of a decline in the physical quality of the resource as ρ_k increases towards 1, i.e. as the resource is depleted.

$$EROI_k = \varepsilon_k * F(\rho_k) = \varepsilon_k * G(\rho_k) * H(\rho_k) \tag{11}$$

Technological component $G(\rho_k)$

In Dale et al. (2011) the technological component $G(\rho_k)$ is a strictly concave function that increases with the exploited resource ratio ρ_k. We replace this formulation by a sigmoid increasing functional form (S-shape curve) that is more in accordance with the historical technological improvements observed by Smil (2005) in the energy industry. Such a formulation is thus convex at the beginning of the resource exploitation, reaches an inflexion point, and then tends asymptotically towards a strictly positive upper limit (Figure 12). Hence, our formulation follows the precepts of the original $G_{Dale\ et\ al.(2011)}(\rho_k)$ component of Dale et al. (2011): first, that there is some minimum amount of energy that must be embodied in the energy extraction device; second, that there is a limit to how efficiently a device can extract energy. In other words we assume that as a technology matures, i.e. as experience is gained, the processes involved become better equipped to use fewer resources (e.g. PV panels become more efficient and less energy intensive to produce; wind turbines become more efficient and increasing size allows exploitation of economies of scale). In our new formulation this technological learning is slow at first and must endure a minimum learning time effort before taking off. Moreover, as in Dale et al.'s (2011) original function, our formulation represents the fact that EROI increases from technological improvements are subject to diminishing marginal returns up to a point where processes approach fundamental theoretical limits (such as the Lancaster-Betz limit in the case of wind turbines). In equation (12) we have reported the original functional expression found in Dale et al. (2011) that we have called here $G_{Dale\ et\ al.(2011)}(\rho_k)$ in order to make a distinction with the function $G(\rho_k)$ that corresponds to the new technological component of the EROI theoretical model.

$$G_{Dale\ et\ al.(2011)}(\rho_k) = 1 - \Psi_k * \exp(-\psi_k * \rho_k). \tag{12}$$

$$G(\rho_k) = \Psi_k + \frac{1 - \Psi_k}{1 + \exp\left(-\psi_k(\rho_k - \overline{\rho_k})\right)}. \tag{13}$$

---

production, discovered reserves and undiscovered resource". On the other hand, Sorrell et al., (2010) highlight that unlike reserves, URR estimates are not dependent on technology assumptions and thus should only be determined by geologic hypotheses. Unfortunately, this apparent contradiction on the URR definition is only a tiny example of the fuzziness of point of views that one could find in the literature regarding the different notions of nonrenewable resources and reserves.

With $0 \leq \Psi_k < 1$ representing the initial normalized EROI with the immature technology used to start the exploitation of the energy source k. ψ_k represents the constant rate of technological learning through experience that depends on a number of both social and physical factors that we do not represent. Finally in our new formulation, $\overline{\rho_k}$ is the particular exploited resource ratio at which the growth rate of the $G(\rho_k)$ is maximum (i.e. the particular value of ρ_k at which $G(\rho_k)$ presents its inflexion point).

Physical depletion component $H(\rho_k)$

The physical resource component of the EROI function, $H(\rho_k)$, is assumed to decrease to an asymptotic limit as cumulated production increases. As advanced by Dale et al. (2011), we follow the argument that on average the production will first be done on resources that offer the best returns (whether financial or energetic) before attention is turned towards resources offering lower returns. Even if this is not completely true at a given moment and for a particular investor, we think that such aggregated behavior, represented by the equation (14), is consistent with long-term economic rationality[7].

$$H(\rho_k) = \exp(-\varphi_k \rho_k). \tag{14}$$

Where $0 < \varphi_k$ represents the constant rate of quality degradation of the energy resource k. Furthermore, we correct a failure of the original function of Dale et al. (2011) consisting in the fact that without more specification the asymptotic limit of $H(\rho_k)$ is zero, which imply following equation (11) that ultimately energy deposits could be exploited with an EROI inferior to unity (as represented in Figure 12). This is in contradiction with the very definition of the URR given previously and with economic rationality. Hence, with the help of the condition find at the end of equation (15), we ensure that the EROI ultimately tends towards 1. In order to find this condition, we first consider that $\lim_{\rho_k \to 1} G(\rho_k) = 1$, hence:

$$\begin{aligned} &\lim_{\rho_k \to 1} EROI_k(\rho_k) = 1 \\ &\Rightarrow \lim_{\rho_k \to 1} \varepsilon_k * H(\rho_k) = 1 \\ &\Leftrightarrow \lim_{\rho_k \to 1} \varepsilon_k * e^{-\varphi_k \rho_k} = 1 \\ &\Rightarrow \varphi_k = \ln(\varepsilon_k) \end{aligned} \tag{15}$$

The condition expressed at the end of (15) also translates in the fact that there is a strictly positive asymptotic limit Φ_k to the decreasing function $H(\rho_k)$, as represented in Figure 12. The value of Φ_k is expressed in (16):

$$\Phi_k = \lim_{\rho_{k \to 1}} H(\rho_k) = \mathrm{e}^{-\varphi_k} = \mathrm{e}^{-\ln \varepsilon_k} = \frac{1}{\varepsilon_k} \tag{16}$$

As shown in Figure 12, the amendments operated on the dynamic function of Dale et al. (2011) avoid two drawbacks of the original formulation: (i) the technological learning that

[7] A more detailed justification of the decreasing exponential functional form given to $H(\rho_k)$, relying on the probability distribution function of the EROI among deposits of the same energy resource is available in Dale et al. (2011).

serves to increases the EROI can now present an increasing S-shape behavior and not a strictly increasing concave form, this is more in accordance with technological diffusion processes; (ii) the exploitation of the energy resource cannot be done with an EROI inferior to unity, which was the case with the original function of Dale et al. (2011) and is contrary to economic rationality as it would means that the energy investors invest more energy, and consequently money, than what they earn from selling their energy production (even if such irrational productive behavior might be possible on discrete production sites and for short time, we postulate that it could not last for long at the aggregated level). However, our new formulation of the theoretical dynamic EROI function makes it more difficult to define the particular value of the exploited resource ratio $\rho_{EROI_k\,max}$ at which the $EROI_k$ is maximum. This value (called P_{max} in the original work of Dale et al., 2011) cannot be found arithmetically anymore (but numerical approximation is off course possible) because of the new functional form we have introduced for the technological component *G*. Nevertheless, as we will see below in paragraph 4.2, the amendments brought to the original theoretical model of Dale et al. (2011) were indispensable to allow its calibration to the historical price-based estimates of the global EROI of coal, oil, and gas previously presented in section 3.

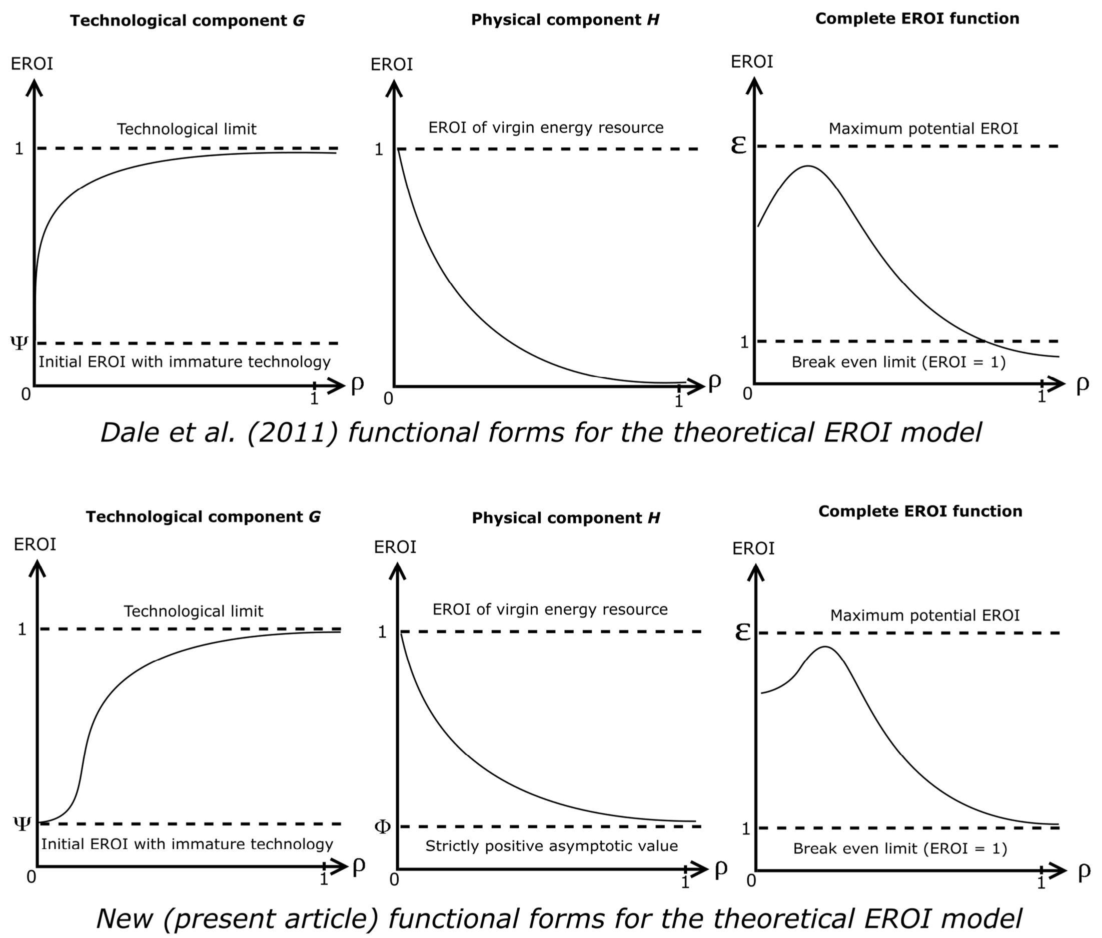

Figure 12. Comparison of the functional forms of the original theoretical EROI model of Dale et al. (2011) and the ones presented in this study after modifications by equations (13) and (15).

4.2 Concordance of our historical estimates of global fossil fuels EROI obtained with the price-based methodology A and the theoretical model

In order to create historical estimates of global EROI for coal, oil, gas, and total fossil fuels with the theoretical model previously presented, we first need to determine their respective exploited resource ratios. Doing so leads to the need of defining the Ultimately Recoverable Resource (URR) of each fossil resource. In the present paper, we define the URR of a given energy resource as the total energy resource that may be recovered at positive net energy yield, i.e. at EROI greater of equal to unity. These values, presented in Table 3, were retrieved from the best estimates of McGlade and Ekins (2015) for oil (Gb: giga barrel), gas (Tcm: terra cubic meters), and coal (Gt: giga tonnes), which for the record are in accordance with the last IIASA Global Energy Assessment report (GEA, 2012). Regarding the coal URR, we find very lower values in other studies, like the average estimate of 1150 Gt (corresponding to 29 500 EJ) given in the literature review of Mohr and Evans (2009). When compared to the order of magnitude of 100 000 EJ found in McGlade and Ekins (2015) and in the GEA (2012), this lower estimation of 29 500 EJ advanced by Mohr and Evans (2009) as an URR corresponds more, in our mind, to a proven reserve estimation. However, we will use this lower coal URR estimate to test the sensitivity of our model to this crucial parameter.

Table 3. Data used for the expression of coal, oil, and gas URR in exajoule. Sources: McGlade and Ekins, 2015.

Energy resource	URR (diverse units)	Conversion factors (diverse units)	URR* (EJ)
Total coal	4085 (Gt)		105 000
63% hard coal	*2565 (Gt)*	*32.5E-9 EJ/tonne*	*83 500*
37% lignite coal	*1520 (Gt)*	*14.0E-9 EJ/tonne*	*21 500*
Total oil	5070 (Gb)		31 000
Conventional oil	*2615 (Gb)*	*6.1E-9 EJ/barrel*	*16 000*
Unconventional oil	*2455 (Gb)*	*6.1E-9 EJ/barrel*	*15 000*
Total gas	675 (Tcm)		27 000
Conventional gas	*375 (Tcm)*	*40 EJ/Tcm*	*15 000*
Unconventional gas	*300 (Tcm)*	*40 EJ/Tcm*	*12 000*
Total fossil fuels			163 000

*URR values expressed in EJ have been round up to the nearest 500.

By combining these URR values with the historical productions of Figure 1, we computed the exploited resource ratios of the fossil fuels as defined by equation (10). Finally, using equations (11) and (13)-(15), we calibrated the "new" theoretical EROI model on each of the historical estimation done with the price-based methodology A for coal, oil, gas and total fossil fuels. Best-fit values for parameters Ψ, ψ, $\overline{\rho}$, and ε are reported in Table 4 and were found using a minimization procedure of the sum of root square errors between the historical estimates of method A and the historical estimates of the theoretical model (value for φ is deduced using the final equivalence of the relation (15)). We have also included the results obtained with a modified version of the original EROI model of Dale et al. (2011) using equation (11), (12), (14), and (15). This "modified Dale et al. (2011) model" consists in taking into account the constraint (14), otherwise two problems appear with the purely original model of Dale et al. (2011): (i) the solver was not capable of finding a solution for coal; (ii) the EROI of gas quickly cross the break-even threshold (i.e. EROI=1:1) after 2033 and then tends towards 0.

Table 4. Parameter values from fitting procedure of the two EROI theoretical models (new and modified Dale et al., 2011) with the historical estimates of price-based methodology A.

Model	Energy resource	Ψ	ψ	$\bar{\rho}$	ε	$\varphi = \ln(\varepsilon)$
New	Coal	0.0601	59.4240	0.0556	205.3599	5.3248
	Oil	0.0000	757.7960	0.0003	45.4368	3.8163
	Gas	0.1169	921.9072	0.0023	134.2093	4.8994
	All Fossil Fuels	0.2916	135.5750	0.0163	49.8173	3.9084
Modified Dale et al. (2011)	Coal	0.9803	2.0567	-	754.2779	6.6258
	Oil	0.5847	515.6436	-	45.5065	3.8179
	Gas	0.9134	398.7105	-	134.2580	4.8998
	All Fossil Fuels	0.6994	51.0909	-	50.1854	3.9157

In Figure 13 we present for the different fossil fuels the comparison between the historical estimates of the global EROI of methodology A and the two theoretical models.

As could have been expected, the theoretical models provide smooth estimations historical fossil fuels EROI. These models also consequently deliver lower values of historical maximum EROI (i.e. peak EROI) for oil, gas, and total fossil. This is summarized in Table 5 where we can also see that the historical time of peaking EROI given by the theoretical models for oil, gas, and total fossil energy are different compared to the ones delivered by the price-based methodology A. Regarding oil, both theoretical models give delayed peaking EROI time compared to the price-based methodology A. However, concerning gas and all aggregated fossil fuels, peaking EROI times given by the new theoretical model precedes the results of the price-based method A, whereas for these same fuels, the modified version of the Dale et al. (2011) model gives slightly lagged (i.e. 1 year) EROI peaking times. Nevertheless, the results of both approached (price based vs. theoretical dynamic models) are consistent regarding their most important results: the maximum EROI of oil, gas and total fossil fuels seemed to have already been reached in the past whereas the maximum EROI of coal has not yet been reached.

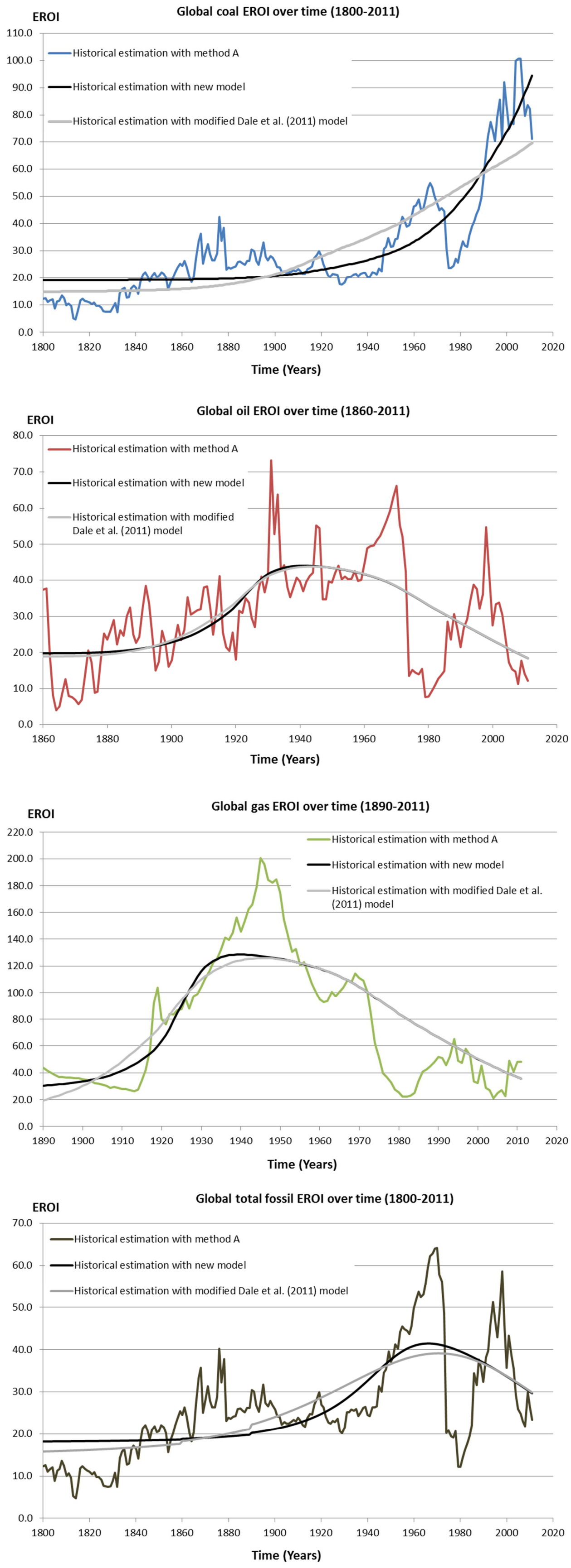

Figure 13. Comparison of the historical estimations of the global EROI of coal, oil, gas, and all fossil fuels between the price-based methodology A and the two theoretical EROI model.

4.3 Some prospects on future fossil fuels global EROI

Doing some prospective assessments of the future global EROI of fossil fuels is possible by extending the estimations of both theoretical models. For that purpose, we first have to choose hypothetical evolutions for the future exploited resource ratios of fossil fuels. We present such hypothetical evolution of the exploited resource ratio of coal, oil, gas, and total fossil energy in Figure 14. Those were obtained by calibrating increasing sigmoid functions[8] to the historical observed[9] exploited resource ratios. We also propose a deviation range for these prospective exploited resource ratios that correspond to a change of ten years in their time of maximum growth rate (i.e. from the base prospective exploited resource ratio, we advance or delay the inflexion point of their representative curves by ten years). Based on these prospective exploited resource ratios and keeping the parameter values of Table 4, we can obtain prospective EROI values for global coal, oil, gas, and total fossil fuels by simply prolonging the theoretical models up to 2150 (Figure 15).

One of the main results of this prospective exercise is the date and value of the peaking coal EROI that logically differs from one theoretical model to another. With the modified Dale et al. (2011) model, global coal EROI peaks in 2043 at 80:1; whereas with our new formulation of the theoretical EROI, we estimate that the global coal EROI will occur sooner in 2030 but at the higher value of 113:1. Hence, both theoretical EROI models support the idea that, since only 10% of global coal resources have been depleted so far, significant energy gains are still to be expected in the coal sector thanks to coming technological improvements. Furthermore, it is also visible in Figure 15 that changing the exploited resource ratio dynamics, i.e. the production profile dynamics at a given URR, does not change the magnitude of the coal EROI peak but only slightly influence the time of this peak. After its peak, the global EROI of coal decreases in a similar way to other fossil fuels. Table 5 synthetized for the three approaches of this study (the price-based method A and the two theoretical EROI models) the time at which the different fossil fuels reach their maximum value and the time at which they cross the particular EROI thresholds of 15:1, 10:1, and 5:1 (the break-even threshold of 1:1 is never formally reached since the constraint (15) imply that both theoretical EROI models tend asymptotically towards this value).

Table 5. Comparison of time and values of maximum EROI and time of EROI crossing thresholds for the different fossil fuels of the two theoretical models and the price-based method A.

Energy Resource	Model	Crossing time EROI=15:1	Crossing time EROI=10:1	Crossing time EROI=5:1	Peak EROI time	Peak EROI value
Coal	New theoretical	2132	2146	2172	2030	113:1
	Modified Dale et al. (2011) theoretical	2139	2152	2170	2043	80:1
	Price-based methodology A	-	-	-	-	-
Oil	New theoretical	2021	2037	2061	1941	44:1
	Modified Dale et al. (2011) theoretical	2021	2037	2061	1944	44:1
	Price-based methodology A	-	-	-	1931	73:1
Gas	New theoretical	2033	2042	2058	1940	129:1
	Modified Dale et al. (2011) theoretical	2033	2042	2058	1946	126:1
	Price-based methodology A	-	-	-	1945	200:1
All Fossil Fuels	New theoretical	2053	2075	2015	1966	42:1
	Modified Dale et al. (2011) theoretical	2053	2075	2015	1971	39:1
	Price-based methodology A	-	-	-	1970	64:1

[8] For a finite resource that necessarily follows a production cycle of Hubbert (1956) type, a sigmoid increasing function characteristically defines its exploited resource ratio.
[9] Recall that historical exploited resource ratios are observed but subjected to the hypotheses made on the URR values.

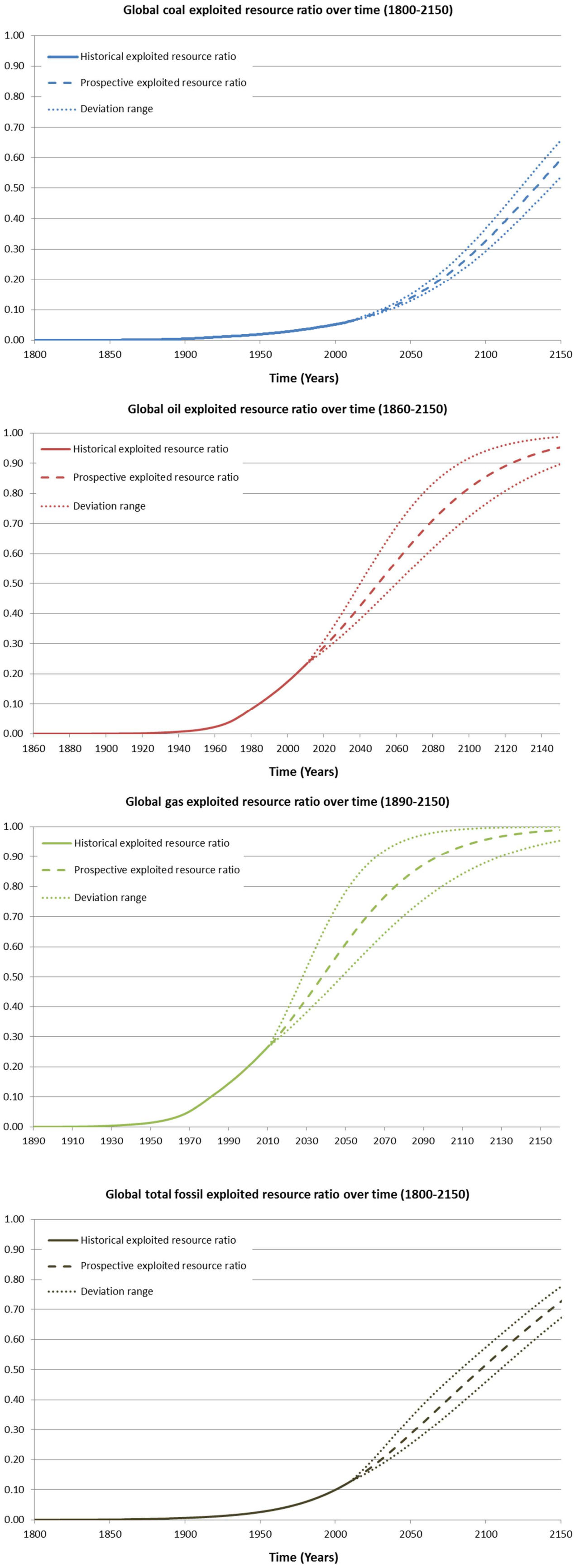

Figure 14. Hypothetical future exploited resource ratio for coal, oil, gas, and all fossil fuels obtained by fitting an increasing sigmoid curve to the historical values. Deviation ranges (dashed lines) are obtains by advancing or delaying by ten years the time of maximum growth rate (i.e. the inflexion point of the S-shape curve).

Given the potentially high controversial aspect of the theoretical EROI model results, in particular regarding the coal prospective outputs, the model sensitivity had to be tested. The key parameter of both theoretical EROI models presented in this study is the value retained for the URR. Let us first notice that, as can be seen in Figure 16 for the case of coal, dividing the URR by three by assuming an URR of 29 500 EJ (equaling the 1150 Gt best estimate advanced by Mohr and Evans, 2009) instead of the previous 105 000 EJ hypothesis, does not change the estimations of the past theoretical EROI from 1800 to 2011. This is because the curve-fitting procedure (minimization of root square errors sum) generate a new set of constant parameters for which the form of the past coal EROI trend remains consistent. However, an URR of 29 500 EJ instead of 105 000 EJ generates a different historical exploited resource ratio (Figure 16) that has consequently a different prospective evolution (still approached by a sigmoid increasing function). Finally, the combination of the alternative prospective exploited resource ratio and the new set of constant parameters generate a different prospective EROI that reaches its maximum EROI sooner, 2021 instead of 2030, and at a lower value, 100:1 instead of 113:1. Nevertheless, considering that this sensitivity analysis has consisted in a 3-fold division of the coal URR estimation, these results can be considered as quite consistent.

Furthermore, it is worth stating that if performed on the other two fossil fuels (oil and gas), the sensitivity analysis consisting in a change of their respective URR would have just change the slope of their decreasing EROI, but under no circumstances a new EROI peak could have been generated. This is mainly due to the fact that by definition in this study, oil and gas comprise both conventional and unconventional fuels since estimations of historical productions of unconventional fuels are really scarce. Yet, giving the increasing prevalence on unconventional fossil fuels in the primary energy mix, it will be needed to perform the analyses of the present paper in few decades. At that time, the importance of future unconventional fossil fuels productions will enable the distinction between conventional and unconventional fossil fuels EROI, which will be of great interests since EROI gains in unconventional fossil fuels production are currently expected. This could show that even if it is certain that maximum EROI have already been reached for conventional fossil fuels, it might not be the case for their unconventional means of production.

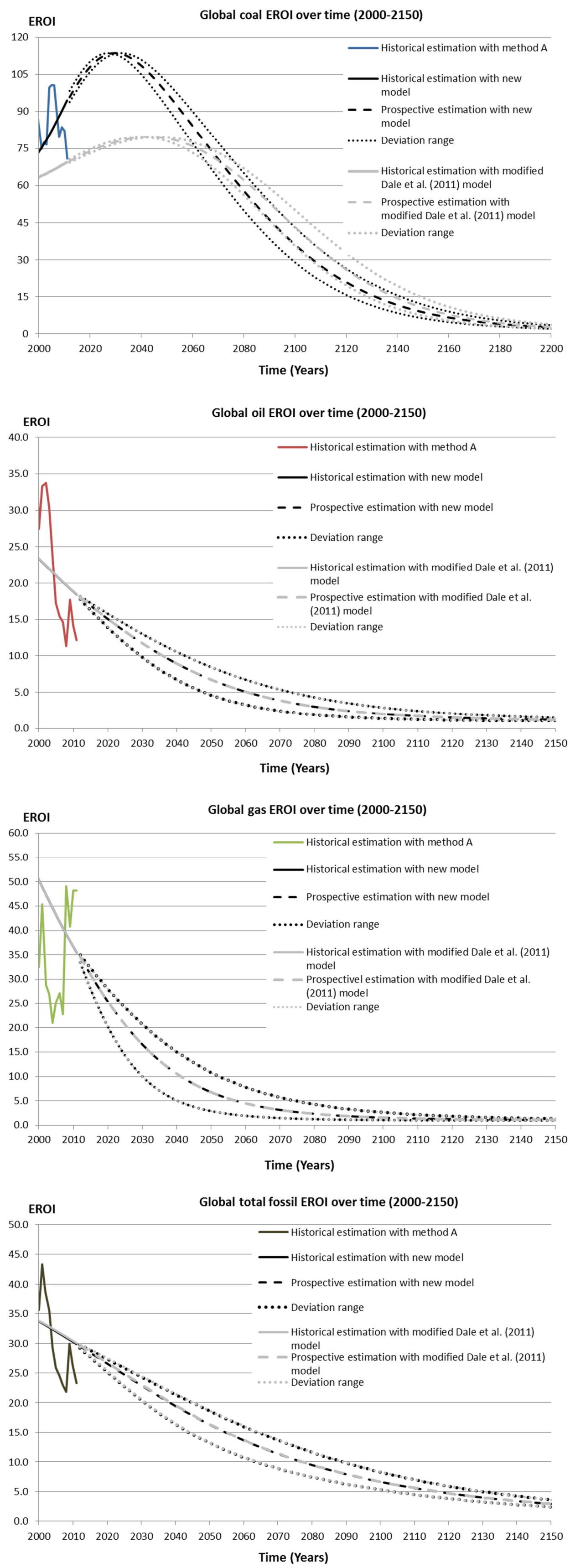

Figure 15. Prospective EROI values for global coal, oil, gas, and total fossil fuels up to 2150 comparing the new and the modified Dale et al. (2011) theoretical models.

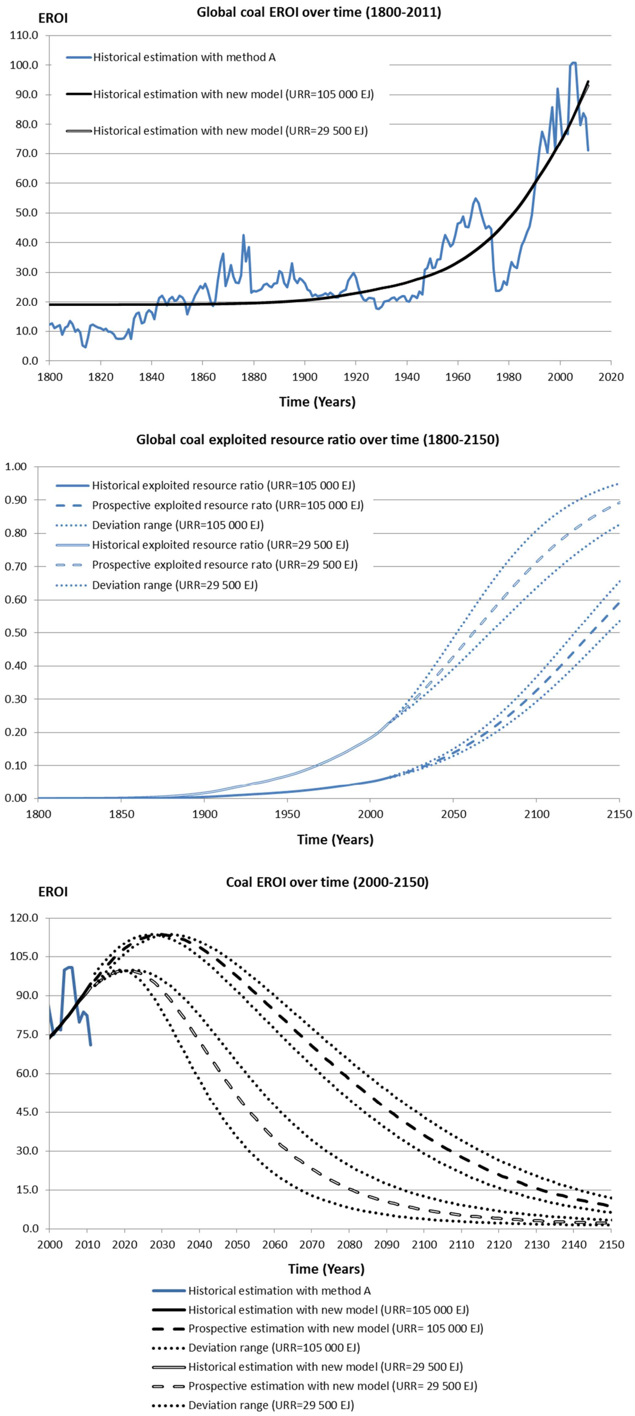

Figure 16. Sensitivity analysis of the "new" theoretical EROI model in the case of coal, using the 29 500 EJ URR estimation of Mohr and Evans (2009) instead of the one of McGlade and Ekins (2015) of 105 000 EJ.

5. Conclusions and research perspectives

In this paper we have filled a gap that needed to be addressed for a while in the EROI literature: estimating the historical global EROI of the different fossil fuels on which humankind has been heavily relying to take the path of industrialization and then service-oriented society. So far indeed, historical EROI trends had been estimated on a few decades at most, and consequently the hypothesis that maximum EROI of fossil fuels had already been reached long ago has been advanced several times without any possible mean of verification. In order to address this problem we have first relied on a price-based approach. By collecting and harmonizing several forms of data, we have provided a very long term historical perspective of (constant 1990$) fossil energy prices in the same energy unit (TJ)[10]. In particular, we have estimated the weighted average price of aggregated fossil energy from 1800 to 2011. Then, thanks to three variant methodologies that proved to deliver consistent results, we have estimated the global EROI of coal, oil, and gas from the beginning of their respective production to 2011, which furthermore allowed us to compute an EROI for the global primary fossil energy sector from 1800 to 2011. The results of this methodology have proved to be consistent with the existing historical estimation of global oil and gas production of Gagnon et al. (2009) made from 1992 to 2006. Good consistence with Cleveland (2005) was also found for what could be considered as the current (i.e. beginning of XXIth century) EROI of coal. Our price-based estimates of global historical fossil fuels EROI have shown that maximum EROI have already been reached for oil and gas, respectively in 1931 at 73:1 and in 1945 at 200:1, whereas the maximum EROI of global coal is still to come. We have then comforted these historical EROI estimates with a comparison to a theoretical expression of the EROI of a given energy resource as a function of its cumulated production. In order to do that, we have first show that the theoretical model originally developed by Dale et al. (2011) needed some amendments to comply with physical reality. Off course, the two theoretical models that we have tested gave much more smoothed trends then the price-based method, but overall a good concordance between the two approaches was observed. This theoretical model also allowed us to perform some prospective estimations of fossil fuels EROI. This work is especially interesting regarding coal since its maximum EROI has not already been reached. The simulations have showed discrepancies among models and URR hypothesis that logically prevent any attempt to determine with assurance the time and the value of the future coal EROI peak. However, considering the several models we have used, and the two very different URR estimations that we have tested, it can be fairly postulated that the maximum coal EROI will occur in a few years or decades between 2020 and 2045, around a value of 110:1.

This study also promotes new avenues for future researches. Indeed, since biomass energy has occupied a central role in the past of industrial economies, and still represents the biggest part of renewable energy at global level by providing an important share of the energy supply in developing countries, estimating the historical EROI of biomass energy should be a research priority. This would allow estimating the global historical EROI of the whole economy from 1800 (or even before) to present times. Unfortunately, since global biomass energy is primarily used in non-commercial channels that are disconnected from markets and their associated prices, another methodology than the one presented in this paper would have to be used. Moreover, our study has focused on primary energy but regarding the fact that

[10] Only the tremendous work of Fouquet (2008) offers a similar historical perspective on energy prices with however a geographical perimeter restricted to the UK.

electricity ensures a growing share of global final energy consumption, we think that future researches should also focus on estimating trends in final and not primary EROI. Finally, as we have based our work on a global view of the economy only, we think it should be really interesting to replicate this work at a national level, in particular in developing countries which are likely to be more sensitive to energy prices.

Acknowledgements

The authors would like to thank Pierre-André Jouvet and Nicolas Legrand for their helpful comments on an earlier version of this article.

References

Ayres, R.U., 1998. Eco-thermodynamics: economics and the second law. *Ecological Economics* 26(2): 189-209.

BP, 2014. *Statistical Review of World Energy*: British Petroleum.

BP, 2015. Oil reserves definition for the Statistical Review of World Energy 2015. Accessed 17/09/15 at: http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2015/oil-reserve-definitions-bp-2015.pdf

Cleveland, C.J., 2005. Net energy from the extraction of oil and gas in the United States. *Energy*, 30, pp. 769-782.

Cleveland, C.J., Costanza, R., Hall, C.A.S., Kaufmann, R., 1984. Energy and the U.S. economy: a biophysical perspective. *Science*, 225, pp. 890-897.

Court, V., Jouvet, P.A, Lantz, F., 2015. Endogenous economic growth, EROI and transition towards renewable energy. Climate Economics Chair, Working paper series, n°2015-07.

Damodaran, A., 2015. Risk/Discount Rate: Total Beta by Industry Sector, Database available at : http://pages.stern.nyu.edu/~adamodar/.

Dale M., S. Krumdieck and P. Bodger, 2011. Net energy yield from production of conventional oil. *Energy Policy* 39, 7095-7102.

Dale M., S. Krumdieck and P. Bodger, 2012. Global energy modelling - A biophysical approach (GEMBA) Part 2: Methodology. *Ecological Economics*, 73, pp. 158-167.

Etemad, B., and Luciani, J. *World energy production, 1800-1985*. Production mondiale d'énergie, 1800-1985. 1991, Genève: Librairie Droz.

Faber, M., 1985. *A biophysical approach to the economy: Entropy, environment and resources*. In: W. van Gool and J. Bruggink (Editors), Energy and Time in Economic and Physical Sciences, pp. 315-337. North-Holland, Amsterdam: Elsevier Sciences Publishers.

Fernandes, S. D., N. M. Trautmann, D. G. Streets, C. A. Roden, and T. C. Bond, 2007. Global biofuel use, 1850 – 2000. *Global Biogeochem. Cycles*, 21, GB2019.

Fizaine, F., Court, V., 2015. Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI. *Ecological Economics*, 110, pp. 106-118.

Fouquet, R. 2008. Heat, Power and Light: revolutions in energy services, Edward Elgar Publications. Cheltenham, UK, and Northampton, MA, USA.

Gagnon, N., Hall, C.A.S., Brinker, L., 2009. A preliminary investigation of the energy return on energy invested for global oil and gas extraction. *Energies*, 2, 490–503.

GEA, 2012. *Global Energy Assessment - Toward a Sustainable Future*. International Institute for Applied Systems Analysis, Vienna, Austria and Cambridge University Press, Cambridge, UK and New York, NY, USA.

Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press, Cambridge, Massachusetts.

Georgescu-Roegen, N., 1979. Energy analysis and economic valuation. *Southern Economic Journal* 45(4): 1023-1058.

Goetzmann, William N., Ibbotson, R. G., Peng , L., 2000. A New Historical Database For The NYSE 1815 To 1925: Performance And Predictability. Yale ICF Working Paper No. 00-13, 45p.

Guilford, M.C., Hall, C.A.S., O'Connor, P., Cleveland, C.J., 2011. A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production. *Sustainability 3*, 1866-1887.

Hall, C.A.S., and Day, J.W., 2009. Revisiting the limits to growth after peak oil. *American Scientist*, 97, pp. 230–237.

Hall, C.A.S, and K.A. Klitgaard, 2006. The need for a new, biophysical-based paradigm in economics for the second half of the age of oil. *International Journal of Transdisciplinary Research* 1(1): 4-22.

Hall, C.A.S., D. Lindenberger, R. Kümmel, T. Kroeger, and W. Eichhorn (2001). The need to reintegrate the natural sciences with economics. *BioScience* 51(8): 663-673.

Hall, C.A.S., Balogh, S., and Murphy, D.J., 2009. What is the Minimum EROI that a Sustainable Society Must Have? *Energies*, 2, pp. 25-47.

Hall, C.A.S., Lambert, J.G., Balogh, S., 2014. EROI of different fuels and the implications for society. *Energy Policy*, 64, pp. 141-152.

Hubbert, K., 1956. Nuclear energy and the fossil fuels. Drilling and Production Practices, American Petroleum Institute. Conference paper originally presented before the Spring Meeting of the Southern District Division of Production, American Petroleum Institute, Plaza Hotel, San Antonio, Texas March 7-8-9, 1956.

Ibbotson, R. G., Sinquefield, R. A., 1976. Stocks, Bonds, Bills, and Inflation: Year-by-Year Historical Returns (1926-1974). *The Journal of Business*, 49 (1), pp. 11-47.

King, C. W., Hall, C. A. S., 2011. Relating Financial and Energy Return on Investment. *Sustainability*, 3, pp. 1810-1832.

Krysiak, 2006. Entropy, limits to growth, and the prospects for weak sustainability. *Ecological Economics* 58, 182-191.

Kümmel, R., 2011. *The Second Law of Economics: Energy, Entropy, and the Origins of Wealth*. Springer-Verlag New York.

Lambert, J., Hall, C., Balogh, S., Poisson, A., Gupta, A., 2012. EROI of Global Energy Resources: Preliminary Status and Trends, Report 1 of 2. UK-DFID 59717, 2 November 2012.

Lambert, J.G., C.A.S., Hall, S., Balogh, A., Gupta, M., Arnold, 2014. Energy, EROI and quality of life. *Energy Policy*, 64, pp. 153-167.

Maddison, A., 2007. *Contours of the World Economy, 1-2030 AD*. Oxford University press.

Manthy, R. S., 1978. *Natural Resource Commodities – A Century of Statistics*, Resources For The Future, The John Hopkins University Press, 244p.

McGlade, C., and P. Ekins, 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature* 57: 187-190.

Mohr, S.H., Evans, G.M., 2009. Forecasting coal production until 2100. *Fuel* 88, 2059-2067.

Murphy, D.J. and Hall, C.A.S., 2010. Year in review – EROI or energy return on (energy) invested. *Annals of the New York Academy of Sciences*, 1185, pp. 102-118.

Murphy, D.J. and Hall, C.A.S., 2011a. Energy return on investment, peak oil, and the end of economic growth in "Ecological Economics Reviews." Robert Costanza, Karin Limburg & Ida Kubiszewski, Eds. *Annals of the New York Academy of Sciences*, 1219, pp. 52-72.

Murphy, D.J. and Hall, C.A.S., 2011b. Adjusting the economy to the new energy realities of the second half of the age of oil. *Ecological Modeling*, 223, pp. 67-71.

O'Connor, M., 1991. Entropy, structure, and organisational change. *Ecological Economics* 3(2): 95-122.

Odum, H.T., 1971. Environment, Power, and Society. New York: Wiley-Interscience, 331 pp.

Odum, H. T., 1973. Energy, Ecology, and Economics. *AMBIO*, 2 (6), pp. 220-227.

Officer, L.H., 2015. What Was the Interest Rate Then?, MeasuringWorth, available at : http://www.measuringworth.com/interestrates/.

Officer, L. H., Williamson, S. H., 2015. The Annual Consumer Price Index for the United States, 1774-2014, MeasuringWorth, available at: http://www.measuringworth.com/uscpi/.

Perrings, C., 1987. Economy and Environment: A Theoretical Essay on the Interdependence of Economic and Environmental Systems. Cambridge : Cambridge University Press.

Rühl, C., Appleby, P., Fennema, J., Naumov, A., Schaffer, M., 2012. Economic development and the demand for energy: A historical perspective on the next 20 years. *Energy Policy* 50, 109-116.

Smil, V., 2005. *Creating the Twentieth Century: Technical Innovations of 1867-1914 and Their Lasting Impact*. New York: Oxford University Press.

Smil, V., 2010. Energy Transitions: History, Requirements, Prospects. Praeger Publishers Inc.

Sorrell, S., J. Spiers, R. Bentley, A. Brandt, R. Miller, (2010). “Global oil depletion: a review of the evidence”. *Energy Policy* 38(9): 5290–5295.

The Maddison Project, http://www.ggdc.net/maddison/maddison-project/home.htm, 2013 version.

The Shift Project, http://www.tsp-data-portal.org/Energy-Production-Statistics#tspQvChart, 2014 version.

United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, DVD Edition.

US Bureau of the Census, 1975. Historical Statistics of the United States, Colonial Times to 1970. Bicentennial Edition, Washington, D.C.

US Energy Information Administration (EIA), 2012a. US Coal Price, available at: http://www.eia.gov/coal/data.cfm#prices.

US Energy Information Administration (EIA), 2012b. US Natural Gas Wellhead Price, available at: http://www.eia.gov/naturalgas/data.cfm#prices.

US Energy Information Administration (EIA), 2014. Database of the U.S. Energy Information Administration called International Energy Statistics, http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm.

WORKING PAPER

n° 2015-10 • Octobre 2015

Climate Economics Chair
Paris-Dauphine University
CDC Climat

LATTER ISSUES

Working Paper Publication Director: Philippe Delacote

La Chaire Economie du Climat est une initiative de CDC Climat et de l'Université Paris-Dauphine sous l'égide de la Fondation Institut Europlace de Finance

contact@chaireeconomieduclimat.org