Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions

Victor Court, Florian Fizaine Fizaine

ÉNERGIE ET INNOVATION : RECHERCHE / ÉTUDE & SYNTHÈSE

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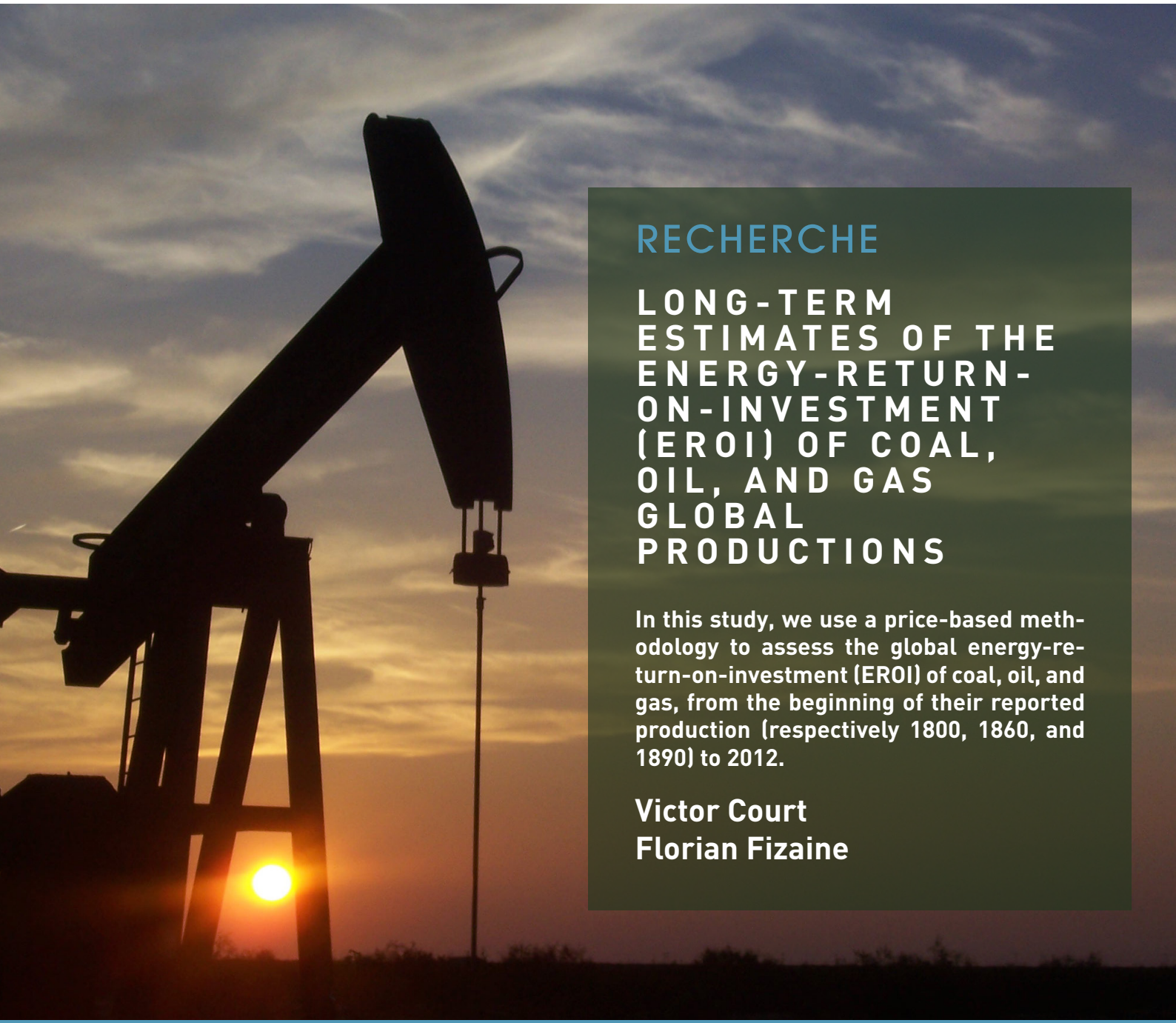

RECHERCHE

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Victor Court
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Pour toute information complémentaire
For any additional information

Victor Court
IFP School
Centre Economie et Management de l'Energie
Energy Economics and Management Center
victor.court@ifpen.fr
Tél +33 1 47 52 73 17

Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions

Victor COURT[a,b,c] and Florian FIZAINE[d]

[a] *EconomiX, UMR 7235, UPL, Univ. Paris Nanterre, 200 avenue de la République, 92001 Nanterre cedex, France.*
[b] *IFP Energies Nouvelles, 1-4 avenue de Bois Préau, 92852 Rueil-Malmaison cedex, France.*
[c] *Chaire Economie du Climat, Palais Brongniart, 28 place de la Bourse, 75002 Paris, France.*
[d] *LEDi - Laboratoire d'Économie de Dijon, Univ. Bourgogne Franche Comté, 2 Boulevard Gabriel, 21066 Dijon cedex, France.*

Abstract

We use a price-based methodology to assess the global energy-return-on-investment (EROI) of coal, oil, and gas, from the beginning of their reported production (respectively 1800, 1860, and 1890) to 2012. It appears that the EROI of global oil and gas productions reached their maximum values in the 1930s–40s, respectively around 50:1 and 150:1, and have declined subsequently. Furthermore, we suggest that the EROI of global coal production has not yet reached its maximum value. Based on the original work of Dale et al. (2011), we then present a new theoretical dynamic expression of the EROI. Modifications of the original model were needed in order to perform calibrations on each of our price-based historical estimates of coal, oil, and gas global EROI. Theoretical models replicate the fact that maximum EROIs of global oil and gas productions have both already been reached while this is not the case for coal. In a prospective exercise, the models show the pace of the expected EROIs decrease for oil and gas in the coming century. Regarding coal, models are helpful to estimate the value and date of the EROI peak, which will most likely occur between 2025 and 2045, around a value of 95(±15):1.

Key words: fossil fuel prices, fossil fuel EROIs, theoretical EROI function.

JEL classification: N7, Q3, Q4, Q5.

E-mail adresses: victorcourt@free.fr, florian.fizaine@gmail.com.

1. Introduction

1.1 Biophysical economics

The perception 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 Ayres & Warr (2009), Kümmel (2011) and Hall & Klitgaard (2012). In order to support calls for a broad paradigm shift in economics (Faber et al. 1987; Hall et al. 2001; Hall & 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-investment (EROI) has attracted considerable attention since all organisms or systems need to procure at least as much energy as they consume in order to pursue their 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). To the partisans of biophysical economics, it leaves no doubt that the development of industrial societies has been largely dependent on fossil fuels, and in particular on their high EROIs and consequent capacity to deliver large amounts of net energy to society.

1.2 EROI of energy systems and implications for society

Because of the lack of hindsight regarding renewables and unconventional fossil fuels (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 scales.[1] The only EROI study of international scope is the one of Gagnon et al. (2009) concerning the global oil and gas production between 1992 and 2006. Furthermore, EROI time series are most of the time computed on short or mid-term time horizons (a few decades at most). A notable exception to this fact is the EROI assessment of the United States oil and gas industry from 1919 to 2007 performed by Guilford et al. (2011). The results of all these different studies are synthetized in Hall et al. (2014). They all show declining trends during recent decades with maximum EROI reached in the past. As society necessarily turns towards lower quality of conventional 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 in the long run. For these reasons, but mostly for geostrategic reasons and the pollution associated with the use of 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 (Murphy & Hall 2010; Hall et al. 2014). Furthermore, as stated by Fizaine & Court (2015), the EROI of renewable electricity producing technologies is more sensitive that of fossil fuels to the increasing energy cost associated with the extraction of the numerous

1 Time series of fossil fuels EROI found in the literature review of Hall et al. (2014) concern the following productions: United States oil and gas, Canadian oil and gas, Norwegian oil and gas, Mexican oil and gas, Chinese oil, gas and coal, Canadian dry gas and United States dry gas.

common and geologically rare metals required in their construction. Hence, for now, performing an energy transition towards renewable technologies seems to necessarily imply a shift from a higher to a lower EROI supply energy mix (i.e. a decrease of the societal EROI). The consequences of this pattern on society remain unclear, but it necessarily raises some serious concerns since our complex, industrialized societies have been built on the use of high quality fossil energy resources, and that the dependence of the economy on its fossil energy supply could potentially have huge adverse effects on its capacity for development (Court et al. 2017).

1.3 Missing perspective, goal, and content

These facts have already been discussed in broader discussions regarding the potential for long-term sustainable development of modern societies (Hall & Day 2009; Hall et al. 2009; Murphy & Hall 2010; 2011a; 2011b; Lambert et al. 2014); but it is worth emphasizing that the EROI of the different fossil energy types used in the economy have never been formally estimated from their respective starting time of production to the present. To achieve such a goal, we use in the current paper a methodology based on the relation of inflation-corrected price and EROI, as first given in King & Hall (2011). Our methodology delivers estimates of the global EROI of coal, oil, and gas, from the beginning of their reported production (respectively 1800, 1860, and 1890) to 2012. In order to do that, we have first had to recover different coherent time-series for the same time periods, concerning:

- the energy prices of the different fossil energy types,
- the global primary energy mix,
- the monetary-return-on-investment of the energy sector or MROI (i.e. the gross margin equals to "1 + the gross margin rate"; meaning that if the gross margin rate is 20%, the corresponding MROI is 1.2),
- the energy intensity of capital expenditures 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 2012, and to subsequently build time-series estimates 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. In this section we also 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). The results of the price-based EROI estimates of global coal, oil, and gas productions are presented and commented in Section 3. While some of our results clearly support educated guesses advanced in previous papers about global oil and gas (namely, that their maximum EROI has already been reached in the past), our results regarding global coal EROI are quite innovative and counterintuitive. We then confront these historical price-based estimates to the theoretical EROI models elaborated from the original work of Dale et al. (2011). In Section 4, we discuss some biases of our methodology and assess the robustness of our results with a comparison to previous existing studies. Finally, in Section 5, we conclude and propose some research perspectives which would be worth investigating as an extension of the present work.

2. Methods

2.1 Price-based estimation of historical fossil fuels global EROI

System boundary

Before specifying our methodology, we follow King et al. (2015) to highlight that the EROI we estimate in this article should be more properly conceptualized as a "Gross Power Return Ratio" since it represents the ratio of annual gross energy produced to annual energy invested. In the strict meaning of the term, the global EROI of a given fossil fuel (expressed as the ratio of cumulated energy production to total energy invested) will be computable only once the last unit of this fossil energy will be extracted from the Earth. Hence, in the present study we estimate annual (or "yearly") EROIs, which thus abstract from the fact that some of this year's production is from prior year's investments, and some of this year's investment will result in future production. We used the EROI denomination for convenience but we recommend the reader to consult the work of King et al. (2015) to get things straight on the various computable energy ratios that exist and the way they relate to each other.

Regarding the output boundary of our study, it is clear considering our methodology that the different EROIs we estimate are all at the mine-mouth or well-head since they concern primary fossil energy. Concerning the input boundary of our study, since we rely on a price-based approach, it makes sense to think that such a price of primary fossil energy covers: direct energy expenditures, indirect energy expenditures from physical capital investment, and indirect energy embodied in what workers purchase with their paycheck (i.e. the energy used to provide food, shelter, transport, and all other things consumed by workers) since wages paid to workers in the energy sector are covered by energy prices. As a consequence, if we refer to the nomenclature of Murphy et al. (2011), the different energy ratios we estimate in this article correspond to "annual $EROI_{1,labor}$".

Equations

Our methodology to estimate the EROI of global primary fossil energy system over time is inspired by the work of King & Hall (2011). For a given year, the $EROI_i$ (unitless) of the fossil energy sector, with $i \in (Coal, Oil, Gas)$, can simply be expressed as the ratio of the energy produced $E_{out,i}$ (expressed in exajoule, or EJ) to the energy $E_{in,i}$ (EJ) invested in the energy sector *i*:

$$EROI_i = \frac{E_{out,i}}{E_{in,i}}. \quad (1)$$

Estimating the i different energy output $E_{out,i}$ is rather simple since databases for coal, oil, and gas historical productions are quite reliable. On the other hand, estimating the energy $E_{in,i}$ invested in each energy sector is far more difficult, especially in long-term analyses. Regarding the global economy, it can be proposed that the energy $E_{in,i}$ (EJ) invested in the global energy system i corresponds to the quantity of money $M_{in,i}$ (expressed in million International Geary-Khamis 1990 dollar,[2] or M$1990) invested in this sector multiplied by the average energy intensity EI_i (EJ/M$1990) of capital and services installed and used in the

2 The International Geary-Khamis 1990 dollar, more commonly known as the international dollar (properly abbreviated Int. G-K. $1990, and more simply $1990 in this study), is a standardized and fictive unit of currency that has the same purchasing power parity as the U.S. dollar had in the United States in 1990.

energy sector i (i.e. the *direct* energy consumption of the energy sector i, plus the *indirect* quantity of energy consumed by the economic system to generate a unitary dollar consequently spent as capital and services installation and use in this same energy sector). Hence, (1) is rearranged as

$$EROI_i = \frac{E_{out,i}}{M_{in,i} * EI_i}. \quad (2)$$

Of course, the problem now lies in estimating the quantity of money $M_{in,i}$ invested in the global energy sector for which very few data exist. Thus, we assume that the unitary price P_i (M$1990/EJ) of a given energy type divided by the monetary-return-on-investment or $MROI_i$ (unitless) of the energy sector i is a proxy for $C_{prod,i}$, the annual (and not levelized) production cost of this same energy. This allows us to estimate the total money $M_{in,i}$ invested in a given energy sector by multiplying the quantity of energy produced $E_{out,i}$ by this sector with the proxy annual cost of this same energy:

$$M_{in,i} = C_{prod,i} * E_{out,i} = \frac{P_i}{MROI_i} * E_{out,i}. \quad (3)$$

By injecting (3) into (2), we obtain that, for each year, the estimated $EROI_i$ at global level is

$$EROI_i = \frac{MROI_i}{P_i * EI_i}. \quad (4)$$

Due to data availability, we have to make two further important assumptions. First, the $MROI_i$ of all i energy sectors are the same and correspond to an average MROI of the fossil energy sector. In Section 4.1, we test three different possibilities to estimate this MROI. They deliver very similar results and show that our EROI estimates are almost insensitive to the MROI because the influence of the price and the energy intensity are far more important. Second, the energy intensities EI_i of all i energy sectors are the same and correspond to the average energy intensity EI of the global economy. In the discussion of Section 4.1, we also test the sensitivity of our results to this assumption because it is very likely that the different expenditures of the global fossil energy sector present an overall higher energy intensity than the average expenditures of the global economy. The global energy intensity EI logically evolves over time and it can be easily computed for a given year as

$$EI = \frac{\sum_j E_{out,j}}{GWP}, \qquad j \in (Coal, Oil, Gas, Nuclear, All\ renewables) \quad (5)$$

where GWP (M$1990) is the gross world product. As shown in (5), 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, wood, wastes). It follows from these assumptions that (4) becomes

$$EROI_i = \frac{MROI}{P_i * EI}. \quad (6)$$

Then, estimating the global $EROI_{All\ fossil\ fuels}$ of the total primary fossil energy sector is straightforward,

$$EROI_{All\ fossil\ fuels} = \frac{MROI}{P_{All\ fossil\ fuels} * EI}. \quad (7)$$

Here $P_{All\ fossil\ fuels}$ (M$1990/EJ) represents the average price of fossil energy weighted by the different quantities of produced fossil energies defined by

$$P_{All\ fossil\ fuels} = \sum_i P_i \frac{E_{out,i}}{\sum_i E_{out,i}}. \quad (8)$$

The methodology presented above requires having consistent time series for: energy quantities (EJ), energy prices (M$1990/EJ), gross world product (M$1990), and an estimation of the monetary-return-on-investment (unitless) of the fossil energy sector.

Data

We used several sources summarized in Table 1 in order to estimate the prices of coal, crude oil, and gas. Because, those prices were originally expressed in very different units, we performed conversions so that all prices are expressed in $1990/TJ (here terajoule, or TJ, is used instead of exajoule for graphical convenience, see Figure 1 and 2). Unfortunately, as shown in Table 1, most of existing long-term time series of energy prices concern United States markets. We nevertheless use these data as global proxies by considering that international markets are competitive and that large spreads between regional energy prices cannot last for long due to arbitrage opportunities. This assumption is fairly relevant for oil and gas, especially in the post World War I period. On the other hand, the hypothesis that coal follows a single international price is a rather coarse assumption. Indeed, as coal is really costly to transport, spreads between prices of two different exporting countries have necessarily occurred, especially before 1950. Furthermore, by using a unique price for coal, we do not take into account the manifold qualities of coal (from the high energy content of anthracite to the lowest quality of lignite). As our coal price estimate is representative of anthracite (high quality), our coal EROI is likely a low estimation of the "true" EROI of coal because we surely slightly overestimate the exact quality-weighted global average price of coal. To make things right, we should have computed such a quality-weighted global average price of coal. This would have been possible if we had known both the shares of all the different coal qualities in the total global coal production (i.e. the quality mix of the global coal supply) and their respective prices, for each year between 1800 and 2012. Unfortunately, to our knowledge, such data is not available. In order to express all energy prices in the same convenient unit, i.e. Int.G-K.$1990 per terajoule ($1990/TJ), we have used the US Consumer Price Index found in Officer & Williamson (2016) and different energy conversion factors such as: the average energy content of one barrel of crude oil (5.73E-03 TJ[3]), the average energy content of one tonne of coal (29.5E-03 TJ), and the average energy content of one thousand cubic feet of gas (1.05E-03 TJ).

3 It is sometimes stated in publications that the calorific content of one barrel of crude oil is 6.2 GJ. Yet, the Statistical Review of World Energy of British Petroleum (2015) gives the value of 42 GJ per tonne of oil equivalent (toe), which corresponds to 7.33 barrels of oil. As a consequence, the calorific content of one barrel of oil is 42/7.33 = 5.73 GJ.

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

Energy	Time and spatial coverage	Source	Original unit
Coal	1800–2012: US average anthracite price.	US Bureau of the Census (1975, pp.207–209) from 1800 to 1948. EIA (2012, p.215) from 1949 to 2011. EIA (2013, p.54) for 2012.	Nominal \$/80-lb. from 1800 to 1824, then nominal \$/short ton.[4]
Oil	1860–1944: US average; 1945–1983: Arabian Light posted at Ras Tanura; 1984–2012: dated Brent.	British Petroleum (2015) for the entire period.	Nominal \$/barrel.
Gas	1890–2012: US average price at the wellhead.	US Bureau of the Census (1975, pp.582–583) from 1890 to 1915. Manthy (1978, p.111) from 1916 to 1921. EIA (2016, p.145) from 1922 to 2012.	Nominal \$/thousand cubic feet.

Figure 1 presents the different time series of fossil energy prices for coal, oil, and gas expressed in \$1990/TJ. Using (8) we have computed from 1800 to 2012 an estimate of the average quantity-weighted price of primary fossil energy (Figure 2). For this purpose we retrieved primary energy production values through the online data portal of The Shift Project (2015) which is built on the original work of Etemad & Luciani (1991) for the 1900–1980 time period and EIA (2014) for 1981–2012. Prior to 1900, we have completed the different fossil fuel time series with the original 5-year interval data of Etemad & Luciani (1991) and filled the gaps using linear interpolation. The work of Fernandes et al. (2007) and Smil (2010) were used to retrieve historical global consumption of traditional biomass energy (woodfuel and crop residues[5]) (Figure 3).

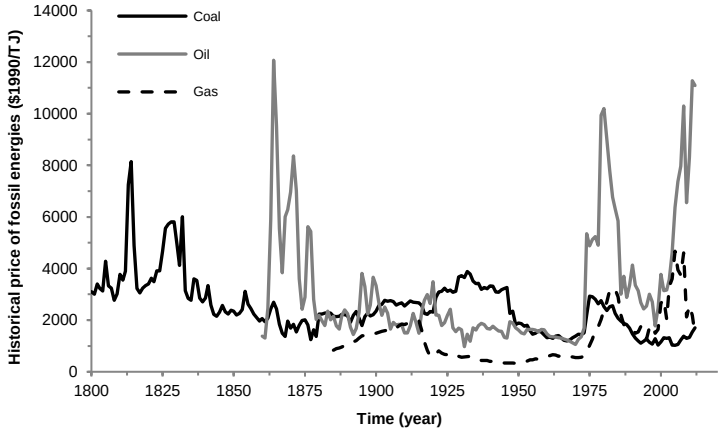


Figure 1. Estimates of global energy prices for coal (1800–2012), oil (1860–2012) and gas (1890–2012) in \$1990/TJ.

4 1 metric tonne = 1000 kg = 1.10231 short ton; 80-lb. = 36.29 kg.

5 Contrary to popular belief, woodfuel and crop residues still represents 70% of the global renewable energy production nowadays, whereas hydro accounts for 20% and new renewable technologies such as wind power, solar PV, geothermal and modern biofuels make up the remaining 10%. Furthermore, global historical estimates of traditional biomass energy used in this paper exclude fodder supplied to draft animals, traditional windmills, and water wheels.

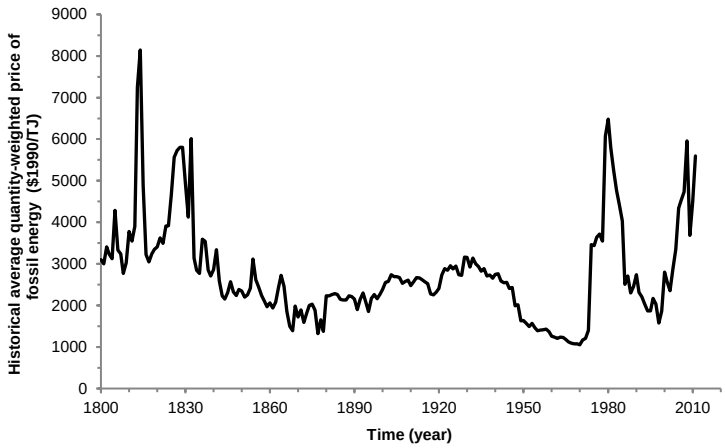


Figure 2. Estimation of the global average quantity-weighted price of fossil energy in $1990/TJ, 1800–2012.

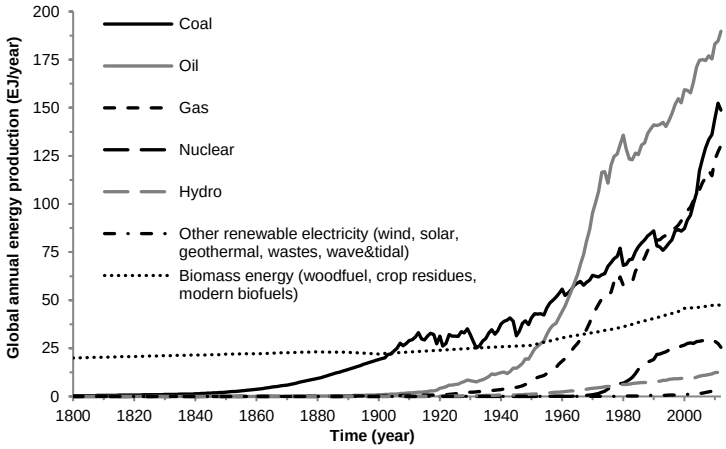


Figure 3. Global annual energy productions (EJ/year), 1800–2012. Data sources: Etemad & Luciani (1991), Fernandes et al. (2007), Smil (2010), EIA (2014), The Shift project (2015).

The gross world product (GWP) of Figure 4 comes from Maddison (2007) from 1800 to 1950 and from the GWP per capita of The Maddison Project (2013) multiplied by the United Nations (2015) estimates of global population from 1950 to 2010. In order to obtain GWP estimates for 2011 and 2012 we used the real GWP growth rate of the World Bank (2016). Dividing the GWP of Figure 4 by the sum of the primary energy productions of Figure 3 yields the average energy intensity of the global economy presented in Figure 5 (expressed here for convenience in MJ per Int. G-K. $1990). We also present in Figure 5 the energy intensity of the global economy over time when the consumption of traditional biomass energy (woodfuel, crop residues) is not accounted for as seen in some studies (e.g. Rühl et al. 2012). To our mind, not taking into account traditional biomass energy in the calculation of a macroeconomic energy intensity is an important mistake. Finally, we follow Damodaran (2015) who claims that the US fossil energy sector monetary-return-on-investment (MROI) roughly follows the US long-term interest rate (US.LTIR retrieved from Officer 2016) with a 10% risk premium. Hence, we compute the MROI of Figure 6 following:

$$MROI = 1 + ((US.LTIR + 10)/100) \quad (9)$$

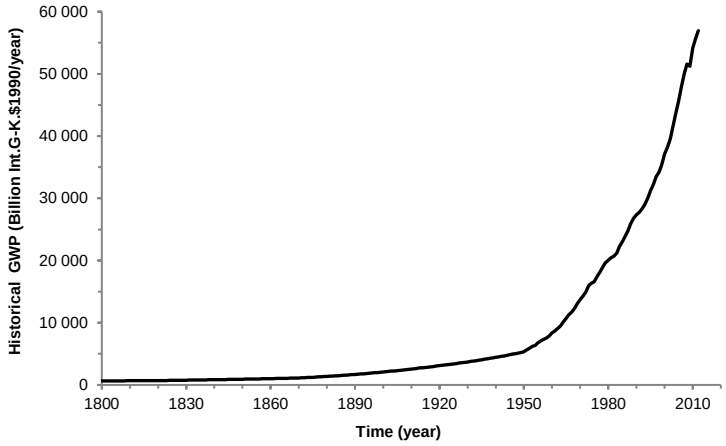


Figure 4. Gross world product (GWP) in billion international Geary–Khamis 1990 dollars, 1800–2012. Data sources: Maddison (2007), The Maddison Project (2013), United Nations (2015), World Bank (2016).

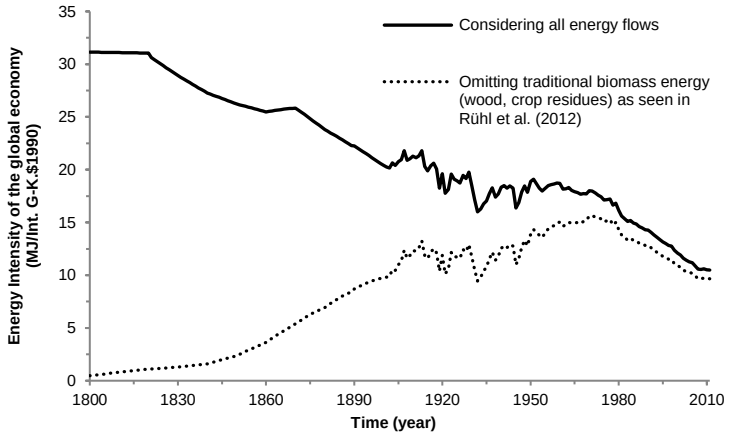


Figure 5. Comparison of the energy intensity of the global economy over time (MJ/Int. G-K.$1990) when traditional biomass energy (woodfuel, crop residues) is accounted for or not, 1800–2012.

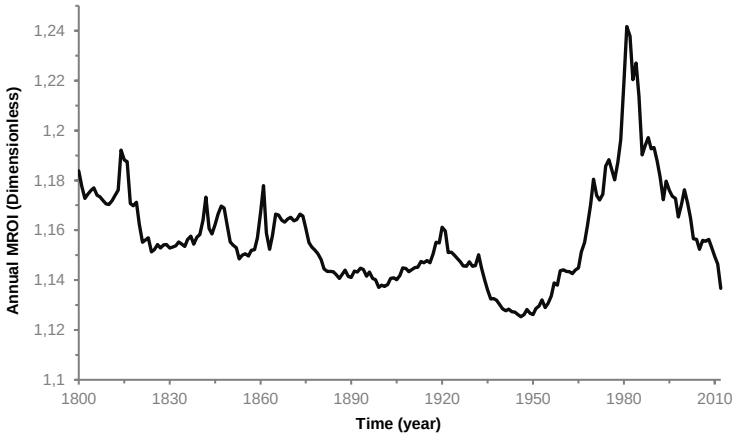


Figure 6. Estimated average annual MROI of US energy sector, 1800–2012. Data source: Officer (2016).

2.2 A new theoretical dynamic model of 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 utilization. Despite the use of such a functional expression of the EROI in a broader theoretical model called GEMBA (Dale et al. 2012), the accuracy of this theoretical model compared to historical EROI estimates of fossil fuels has never been tested. Since in Section 3.1 we provide such global estimates for the EROI of coal, oil, and gas from their respective beginnings of production to present time, we can compare these results with the original theoretical model of Dale et al. (2011). In trying to do so, we found that this theoretical model needed to be slightly modified in order to correct two drawbacks.

Theoretical considerations

Like Dale et al. (2011) we assume that, for a given year, the annual $EROI_j$ of a given energy resource j (either nonrenewable or renewable) depends on a scaling factor ε_j, which represents the maximum potential EROI value (never formally attained); and on a function $F(\rho_j)$ depending on the exploited resource ratio $0 \leq \rho_j \leq 1$. In the case of nonrenewable energy (but not renewable), ρ_j is also known as the normalized cumulated production, i.e. the cumulated production $CumE_{out,j}$ normalized to the size of the Ultimately Recoverable Resource[6] URR_j defined as the total resource that may be recovered at positive net energy yield, i.e. at EROI greater or equal to unity.

$$\rho_j(nonrenewable) = \frac{CumE_{out,j}}{URR_j} \in [0,1]. \quad (10)$$

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

$$EROI_j(\rho_j) = \varepsilon_j F(\rho_j) = \varepsilon_j G(\rho_j) H(\rho_j). \quad (11)$$

Technological component $G(\rho_j)$

In Dale et al. (2011) the technological component $G(\rho_j)$ is a strictly concave function that increases with the exploited resource ratio ρ_j. We replace this formulation by a sigmoid increasing functional form (S-shaped 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 7). Hence,

6 According to British Petroleum (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 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 of the URR definition is only a tiny example of the fuzziness of points of view that one could find in the literature regarding the different notions of nonrenewable resources and reserves.

our formulation follows the precepts of the original $G_{Dale\ et\ al.(2011)}(\rho_j)$ 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 and wind turbines become less energy intensive to produce, and more efficient in converting primary energy into electricity). 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. (2011)'s 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 $G_{Dale\ et\ al.(2011)}(\rho_j)$ in order to make a distinction with (13) that is the function $G(\rho_j)$ that corresponds to the new technological component of the EROI theoretical model.

$$G_{Dale\ et\ al.(2011)}(\rho_j) = 1 - \Psi_j \exp(-\psi_j \rho_j). \tag{12}$$

$$G(\rho_j) = \Psi_j + \frac{1 - \Psi_j}{1 + \exp\left(-\psi_j(\rho_j - \widetilde{\rho_j})\right)}. \tag{13}$$

With $0 \leq \Psi_j < 1$ representing the initial normalized EROI with the immature technology used to start the exploitation of the energy source j. ψ_j 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, $\widetilde{\rho_j}$ is the particular exploited resource ratio at which the growth rate of $G(\rho_j)$ is maximum (i.e. the particular value of ρ_j at which $G(\rho_j)$ presents its inflexion point).

Physical depletion component $H(\rho_j)$

The physical resource component of the EROI function, $H(\rho_j)$, 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 production first comes from resources that offer the best (financial or energy) returns 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 (14), is consistent with long-term economic rationality.[7]

$$H(\rho_j) = \exp(-\varphi_j \rho_j). \tag{14}$$

Where $0 < \varphi_j$ represents the constant rate of quality degradation of the energy resource j. In the original function of Dale et al. (2011), since there is no additional specification, the

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

asymptotic limit of $H(\rho_j)$ is zero, which implies that ultimately energy deposits could be exploited with an EROI inferior to unity (as represented in Figure 7). Such a production choice could find some justification at national level as it is easy to imagine a country willing to extract a strategic energy resource energy (such as crude oil for instance) with an EROI inferior to unity thanks to another energy input with an EROI far above 1 (such as gas or nuclear electricity for instance). But in a global and long-term future context, it does not make much sense to think that the extraction of a nonrenewable energy resource with an EROI inferior to one will last for long. Economic rationality implies that energy resources can sporadically and locally be extracted with an EROI inferior to unity, but not in the long-run global scale. Hence, with the help of the condition found 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 $\lim_{\rho_j \to 1} G(\rho_j) = 1$, hence:

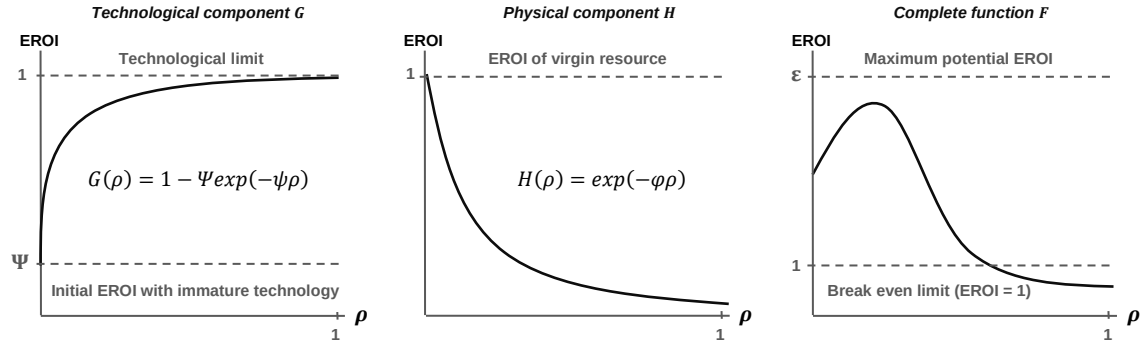
$$\begin{aligned} &\lim_{\rho_j \to 1} EROI_j(\rho_j) = 1 \\ &\Rightarrow \lim_{\rho_j \to 1} \varepsilon_j H(\rho_j) = 1 \\ &\Leftrightarrow \lim_{\rho_j \to 1} \varepsilon_j \, e^{-\varphi_j \rho_j} = 1 \\ &\Rightarrow \varphi_j = \ln(\varepsilon_j). \end{aligned} \tag{15}$$

The condition expressed at the end of (15) also translates into the fact that there is a strictly positive asymptotic limit Φ_j to the decreasing function $H(\rho_j)$, as represented in Figure 7. The value of Φ_j is defined as

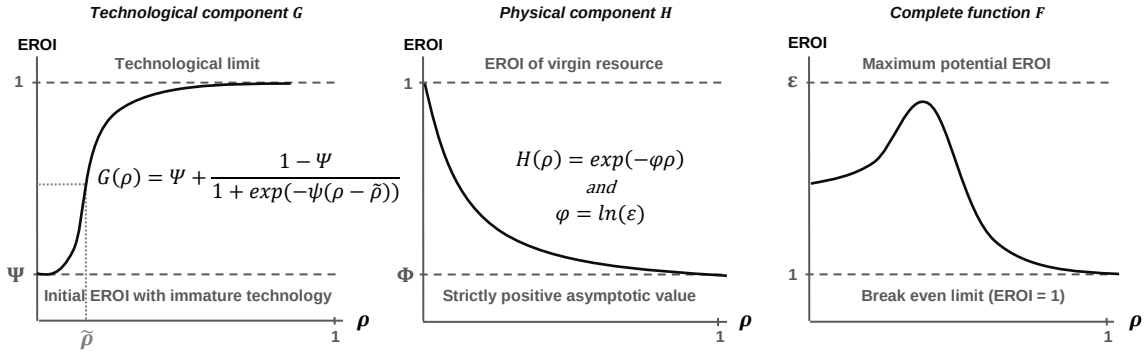
$$\Phi_j = \lim_{\rho_{j \to 1}} H(\rho_j) = \mathrm{e}^{-\varphi_j} = \mathrm{e}^{-\ln \varepsilon_j} = \frac{1}{\varepsilon_j}. \tag{16}$$

As shown in Figure 7, the amendments operated on the dynamic function of Dale et al. (2011) avoid two drawbacks of the original formulation: (i) the technological learning that serves to increase the EROI can now present an increasing S-shape behavior and not a strictly increasing concave form, which is more in line with technological diffusion processes; (ii) the exploitation of the energy resource is not possible 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 in the global and long-term context as it would means that, over several decades, energy investors invest more energy, and consequently money, than they earn from selling their energy production (even if such irrational productive behavior might be possible on discrete

production sites and for a short time).[8] However, our new formulation of the theoretical dynamic EROI function makes it more difficult to define the particular value of the exploited resource ratio $\rho_{EROI_j max}$ at which the $EROI_j$ is maximum. This value cannot be found arithmetically anymore (but numerical approximation is of course possible) because of the new functional form we have introduced for the technological component *G*. Nevertheless, as explained in the coming Section 3.2, the amendments brought to the original theoretical model of Dale et al. (2011) were essential to allow its calibration to the historical price-based estimates of the global EROI of coal, oil, and gas presented in Section 3.1.



Dale et al. (2011) functional forms for the theoretical EROI model



New (present thesis) functional forms for the theoretical EROI model

Figure 7. Dale et al. (2011) vs. new (present article) functional forms for the theoretical EROI 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 implies defining the Ultimately Recoverable Resource (URR) of each fossil resource. In the present paper, we define the URR of a given energy

8 A very important point that is not stressed in Dale et al. (2011) is that the dynamic function of the EROI does not represent the same physical indicator if one considers a nonrenewable or a renewable energy resource. In the case of a nonrenewable energy resource, equation (11) and the right side of Figure 7 describe the average annual EROI with which the nonrenewable energy is extracted from the environment. But in the case of renewable energy, equation (11) and the right side of Figure 7 describe the marginal annual EROI with which the renewable energy is extracted from the environment. For example, if we take the example of oil for the nonrenewable energy resource, the dynamic EROI function described in this section implicates that the last barrel of oil that will be extracted from the ground in the future will have an EROI just above 1. In the case of a renewable energy resource such as wind, the same model means that the last wind turbine that will be installed, and will totally saturate the technical potential of wind energy, will have an EROI just above 1; but of course, in such a future situation the whole annual production of energy from wind turbines will have an average EROI far above 1. This difference is not relevant for our paper, but it is off course very important in the context of the energy transition.

resource as the total energy resource that may be recovered at positive net energy yield, i.e. at EROI greater or equal to unity. These values, presented in Table 2, were retrieved from the best estimates of McGlade & 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 (IIASA 2012). Regarding the coal URR, we found much lower values in other studies, like the average estimate of 1150 Gt (corresponding to 29 500 EJ) given in the literature review of Mohr & Evans (2009). When compared to the order of magnitude of 100 000 EJ found in McGlade & Ekins (2015) and IIASA (2012), lower estimation of 29 500 EJ advanced by Mohr & Evans (2009) as an URR corresponds more, according to us, 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 in Section 4.3.

Table 2. Coal, oil, and gas global URR. Source: McGlade & Ekins, 2015.

Energy resource	**Global URR (diverse units)**	**Conversion factors (diverse units)**	**Global URR* (EJ)**
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*
Oil	5070 (Gb)		29,000
Conventional oil	*2615 (Gb)*	*5.73E-9 EJ/barrel*	*15,000*
Unconventional oil	*2455 (Gb)*	*5.73E-9 EJ/barrel*	*14,000*
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			161,000

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

3. Results

3.1 Price-based estimates of historical fossil fuels global EROI

Figure 8 presents the estimations of the global EROI of coal, oil, gas, and of the total primary fossil energy system obtained with the price-based methodology developed in Section 2.1. Separate graphical representations for each energy type are available in Figure 9. Considering that our approach is based on financial data (prices, MROI) and that (in the absence of any better solution) energy intensity was taken as the average of global society at large, analyses of results shall retain orders of magnitude and trends and absolutely not precise estimated values for given years. It is interesting to see that according to our estimates, and contrary to what common sense would suggest, the global EROI of the three fossil fuels (coal, oil, and gas) were not at their maximum in the early years of their respective (reported) productions. Our estimates show that maximum EROIs seem to have already been achieved in the 1930s–40s for global oil and gas production, respectively around 50:1 and 150:1. EROI of global coal production seems to have broadly increased from 1800 to the present, indicating that maximum EROI has not yet been attained for this energy resource. Furthermore, we can observe in Figure 8 that the global EROI of the total primary fossil energy system has followed the global EROI of coal from 1800 to 1955 and then of oil from 1965 to 2012. 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 production data reported in Figure 3, where it can be found that 1964 is the year during which global oil production exceeded global coal production for the first time.

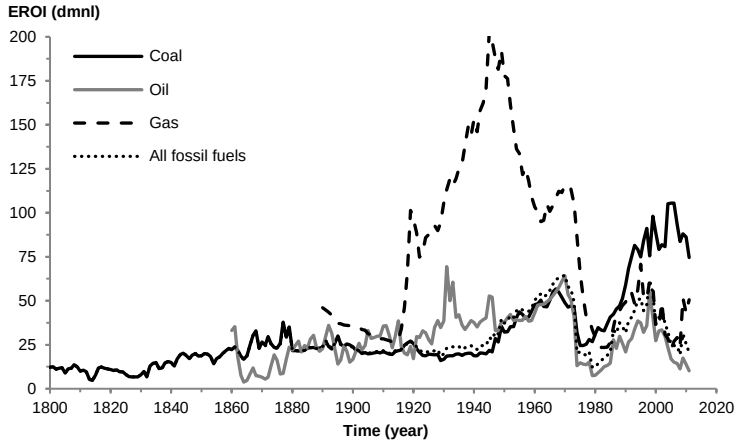


Figure 8. Global EROI of coal, oil, gas, and all fossil fuels estimated with the price-based methodology developed in Section 2.1, 1800–2012.

In order to better analyze the course of these EROI dynamics, we compare in the coming Section 3.2 these price-based EROI estimations to the theoretical dynamic model developed in Section 2.2.

3.2 Theoretical EROI model vs. historical price-based estimates

By combining the URR values of Table 2 with the historical production of Figure 3, we can compute the exploited resource ratios of the different fossil fuels as defined by (10). Then, using (11) and (13)-(15), we calibrated the "new" theoretical EROI model on each of the historical estimates obtained with the price-based methodology for coal, oil, gas and total fossil fuels. Best-fit values for parameters Ψ, ψ, $\overline{\rho}$, and ε are reported in Table 3 and were found using a minimization procedure of the sum of root square errors between the historical estimates of the price-based method and the historical estimates of the theoretical model (value for φ is deduced using the final equivalence of relation (15)).[9] We have also included the results obtained with a modified version of the original theoretical 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 (15), otherwise two problems appeared 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 crosses the break-even threshold (i.e. $EROI = 1$) after 2033 and then tends towards 0.

Table 3. Parameter values of the two EROI theoretical models (new and modified Dale et al., 2011) after calibration on historical price-based estimates.

Model	Energy resource	Ψ	ψ	$\widetilde{\rho}$	ε	$\varphi = \ln(\varepsilon)$
New	Coal	0.0733	70.4688	0.0471	166.2530	5.1135
	Oil	0.0000	658.31543	0.0005	44.3667	3.7925
	Gas	0.2726	7226.013	0.0006	118.8348	4.7777
	All fossil fuels	0.3755	295.9939	0.0208	48.8247	3.8882
Modified Dale et al. (2011)	Coal	0.9844	2.0557	-	818.2974	6.7072
	Oil	0.6016	422.6537	-	44.5658	3.7920
	Gas	0.8506	1641.1808	-	119.7445	4.7854
	All fossil fuels	0.7360	49.3492	-	49.4000	3.9000

9 Robustness of results was tested through a cross validation process: by modifying the data sample (removing some years), parameters of models were re-estimated and proved to remain similar.

As could have been expected, the theoretical models provide smooth estimates of historical fossil fuel EROIs. These models also consequently deliver lower values of historical maximum EROIs (i.e. peak EROI) for oil, gas, and total fossil energy. This is summarized in Table 4 where we can also see that historical EROI peaking-times given by theoretical models for oil, gas, and total fossil energy are different compared to the ones delivered by the price-based methodology. Regarding oil, both theoretical models give delayed peaking EROI times compared to the price-based methodology. However, concerning gas and aggregated fossil fuels, peaking EROI times given by the new theoretical model precede the results of the price-based approach, whereas for these same fuels, the modified version of the Dale et al. (2011) model gives slightly lagged EROI peaking times. Nevertheless, the results of both approaches (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.

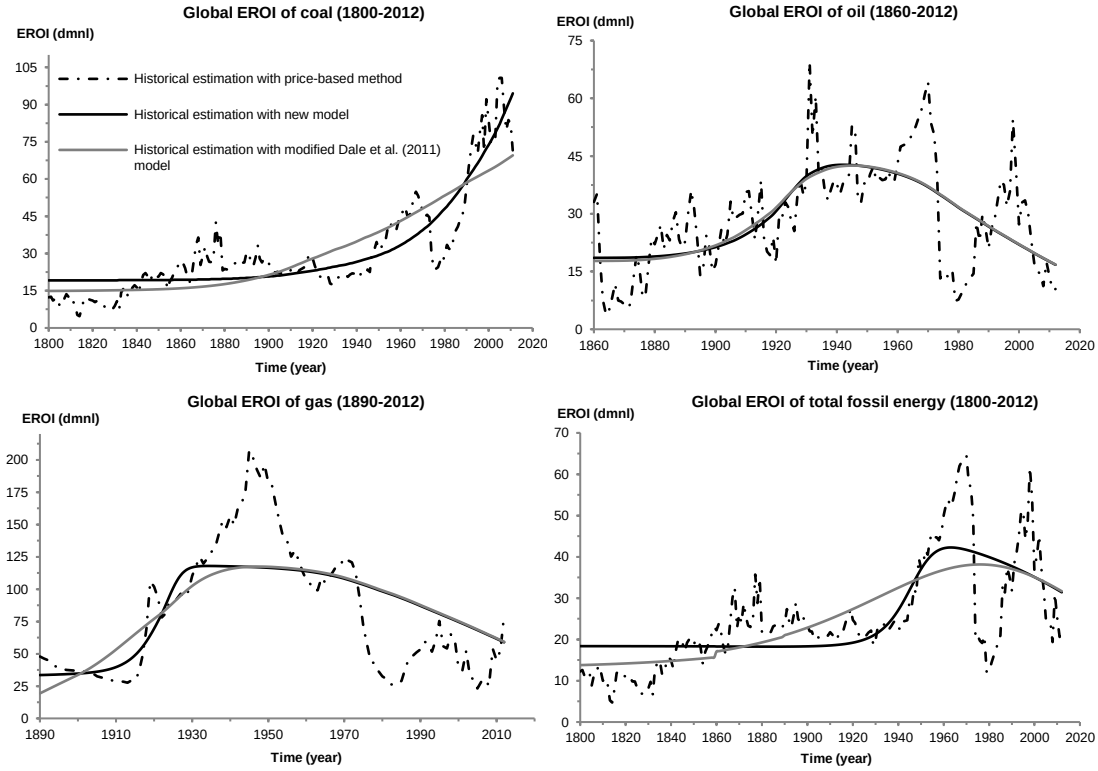


Figure 9. Historical estimates of the global EROI of coal, oil, gas, and all fossil fuels with the price-based methodology and the two theoretical models.

3.3 Some prospects on future fossil fuel global EROIs

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 10. Those were obtained by calibrating increasing sigmoid

functions to the historical observed exploited resource ratios.[10] 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 3, we can obtain prospective EROI values for global coal, oil, gas, and total fossil fuels by simply prolonging the theoretical models up to 2150. As shown in Figure 11, 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 85:1; whereas with our new formulation of the theoretical EROI model, we estimate that the global coal EROI peak will occur sooner in 2023 but at the higher value of 101:1. 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 11 with the deviation range 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 influences the time of this peak. After its peak, the global EROI of coal decreases in a way similar to other fossil fuels.

Table 4 synthetized for the three approaches of this study (the price-based method 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) implies that both theoretical EROI models tend asymptotically towards this value).

Table 4. Time and values of maximum EROI, and time of EROI crossing thresholds for the different fossil fuels with the two theoretical models and the price-based method.

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	2128	2143	2169	2023	101:1
	Modified Dale et al. (2011) theoretical	2140	2153	2177	2043	85:1
	Price-based methodology	-	-	-	-	-
Oil	New theoretical	2018	2035	2061	1943	43:1
	Modified Dale et al. (2011) theoretical	2018	2035	2061	1945	42:1
	Price-based methodology	-	-	-	1931	70:1
Gas	New theoretical	2050	2058	2073	1934	118:1
	Modified Dale et al. (2011) theoretical	2050	2058	2074	1947	117:1
	Price-based methodology	-	-	-	1945	207:1
All fossil fuels	New theoretical	2060	2080	2117	1965	42:1
	Modified Dale et al. (2011) theoretical	2060	2080	2118	1975	38:1
	Price-based methodology	-	-	-	1970	65:1

Note: Even if such accuracy is misleading for the general discussion, the precise estimated peak values of oil (70:1 in 1931), gas (207:1 in 1945), and total fossil energy (65:1 in 1970) delivered by the price-based methodology are included in this table for the sake of completeness and consistency.

10 The exploited resource ratio of a finite resource that necessarily follows a production cycle of Hubbert (1956) type, is quite logically an increasing sigmoid function (i.e. an S-shape curve). Recall that historical exploited resource ratios are observed but subjected to the hypotheses made on URR values.

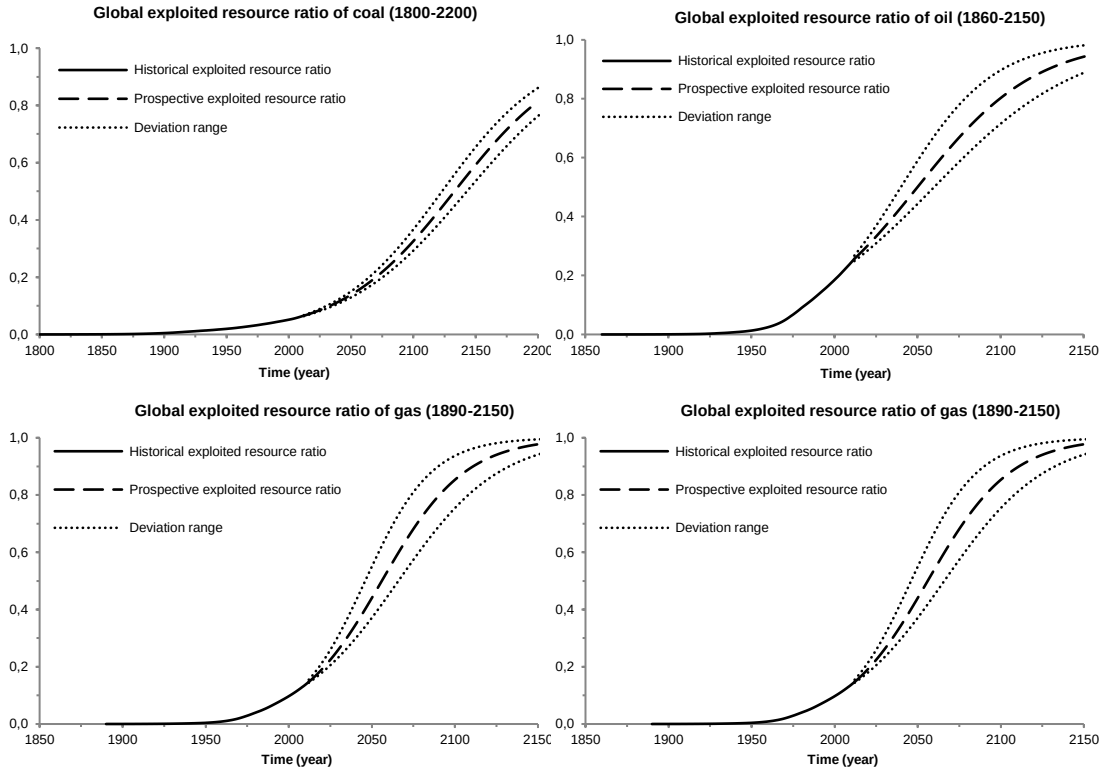


Figure 10. Hypothetical future exploited resource ratio for coal, oil, gas, and all fossil fuels (dashed lines) obtained by fitting an increasing sigmoid curve to the historical values (solid lines). Deviation ranges (doted lines) are obtained by advancing or delaying by ten years the time of maximum growth rate (i.e. the inflexion point of the S-shaped curves).

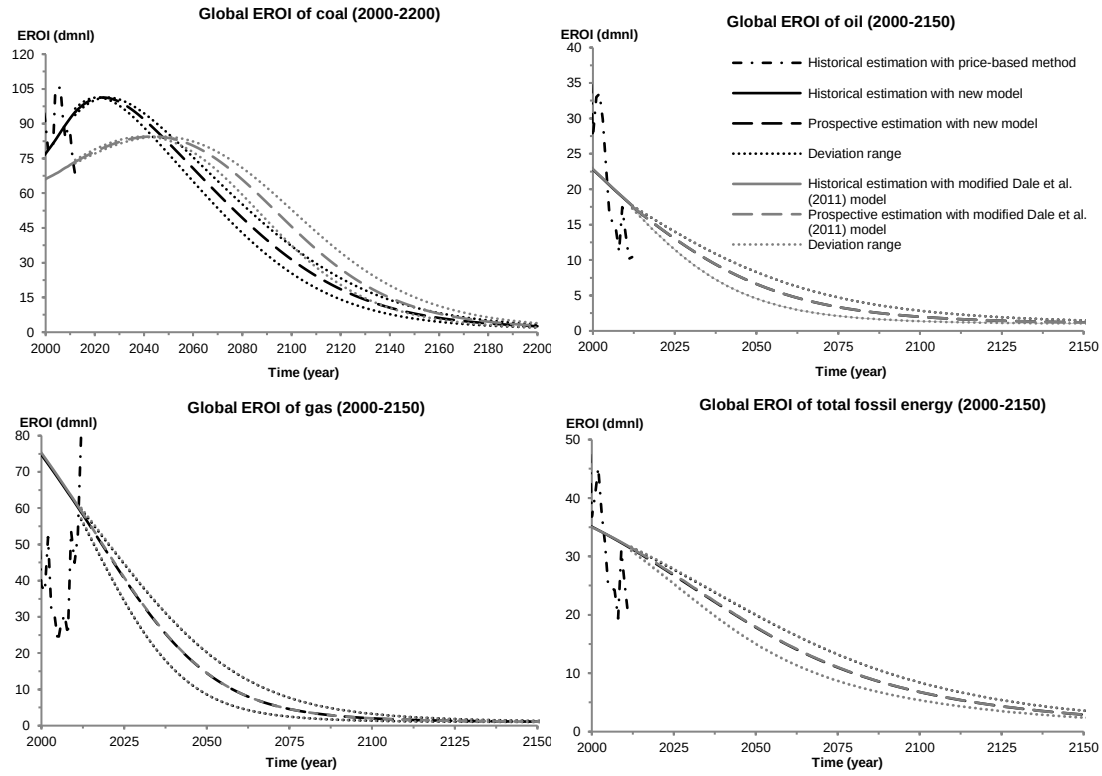


Figure 11. Prospective EROI values for global coal, oil, gas, and total fossil fuels up to 2150 (2200 in the case of coal) comparing the new and the modified Dale et al. (2011) theoretical models.

4. Discussion

4.1 Biases in the price-based approach

As can been seen in equation (6) and (7), our method to estimate the global EROI of fossil fuels is logically sensitive to the uncertainty surrounding the value of its three arguments, namely:

- the prices of fossil energies presented in Figure 1,
- the monetary-return-on-investment (*MROI*) supposed common to all scenarios but varying over time thanks to (9),
- the energy intensity (*EI*) taken as the global economy average and evolving over time as shown in Figure 5.

The different fossil energy prices integrate investment in energy sectors but also different kinds of rents, in particular during temporary exercise of market power. Those are not taken into account in the *MROI* 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 come from historical data that we consider to be robust, we think that our results are mostly subjected to the uncertainties surrounding the *MROI* and the *EI*.

Sensitivity of price-based results to the MROI

Regarding the estimates of the monetary-return-on-investment (*MROI*) in the energy sector, we propose to test two variants of the one used so far that rest on the US long-term interest rate. The three variants are labeled A, B, and C, with the following definition:

- Variant A: the $MROI_A$ is based on the US long-term interest rate (US.LTIR) presented in Figure 6, to which a risk premium of 10% is added following Damodaran (2015).
- Variant B: the $MROI_B$ is based on a reconstructed AMEX Oil Index[11] based on a relation estimated between the AMEX Oil Index of Reuters (2016) for the period 1984-2012 and the NYSE Index annual returns on this same period. NYSE Index annual returns were retrieved from different references: Goetzmann et al. (2001) for the 1815-1925 period, Ibbotson & Sinquefield (1976) for the 1926-1974 period, and NYSE (2015) the 1975-2012 period (Figure 12).
- Variant C: the $MROI_C$ is considered constant and equal to 1.1 (i.e. the energy sector gross margin is 10%). This hypothesis is the one used in previous studies such as King & Hall (2011), and King et al. (2015).

We summarize in Table 5 the different relations employed to estimate the MROI supposed equal (for a given year) in all different fossil energy sectors.

11 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.

Table 5. Synthetic description of the three possible methodology variant A, B, and C used to estimate the MROI of the fossil energy sector.

Variant name	Main assumptions in methodology
A	$MROI_A = 1 + ((US.LTIR + 10)/100)$.
B	$MROI_B = 1 + AMEX\ Oil\ Index_{estimated}$.
C	$MROI_c = 1.1$

Regarding the variant B, the variable $AMEX\ Oil_{estimated}$ is computed following (17). Parameters values of (17) were obtained through a regression of the $AMEX\ Oil_{data}$ of Reuters (2016) on the $NYSE_{data}$ for the period 1984-2012.

$$AMEX\ Oil\ Index_{estimated} = 0.05466 + 0.65233 * NYSE_{data}. \quad (17)$$

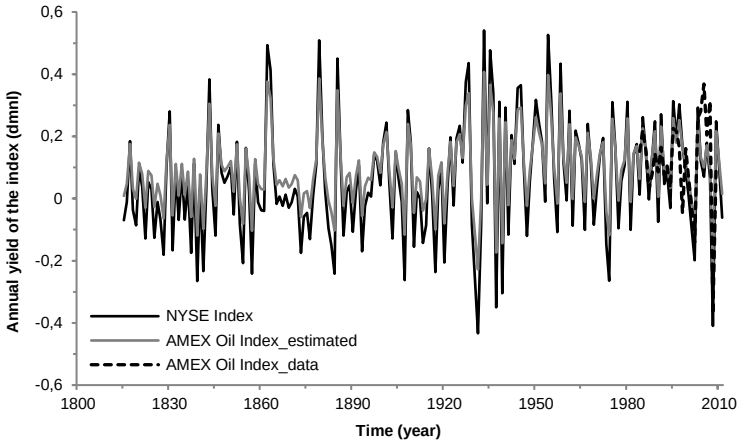


Figure 12. Reconstructed AMEX Oil Index annual yield (grey line) from 1815 to 2012. This variable is obtained with relation (17) where the NYSE Index data (black line) is retrieved from Goetzmann et al. (2001) for the 1815–1925 period, Ibbotson & Sinquefield (1976) for the 1926–1974 period, and NYSE (2015) for 1975–2012. The original AMEX Oil Index data (dashed grey line) of Reuters (2016) is only available for the period 1984–2012.

Figure 13 shows how the three MROI variants A, B, and C evolve over time.

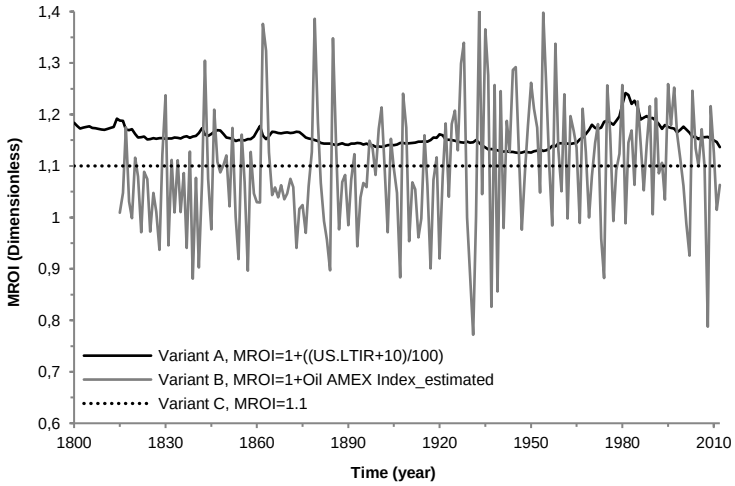


Figure 13. Comparison of the three MROI variants supposed equal among all fossil fuel sectors for a given year.

Figure 14 presents our estimates of the global EROI of coal, oil, gas, and of the total primary fossil energy system with the three possible MROI A, B, and C. It shows that our EROI results are quite insensitive to the MROI variability. Indeed, the three MROI variants deliver very consistent results. When looking at a particular energy type it is difficult to make a distinction between the different EROI estimates because methodological alternatives do not generates large enough output differences. This is particularly true for variant A and C which are hardly discernible. However, it is worth noting that there is a slightly higher volatility in values of variant B (that moreover cannot starts in 1800 because of the impossibility to estimate the $MROI_B$ before 1815).

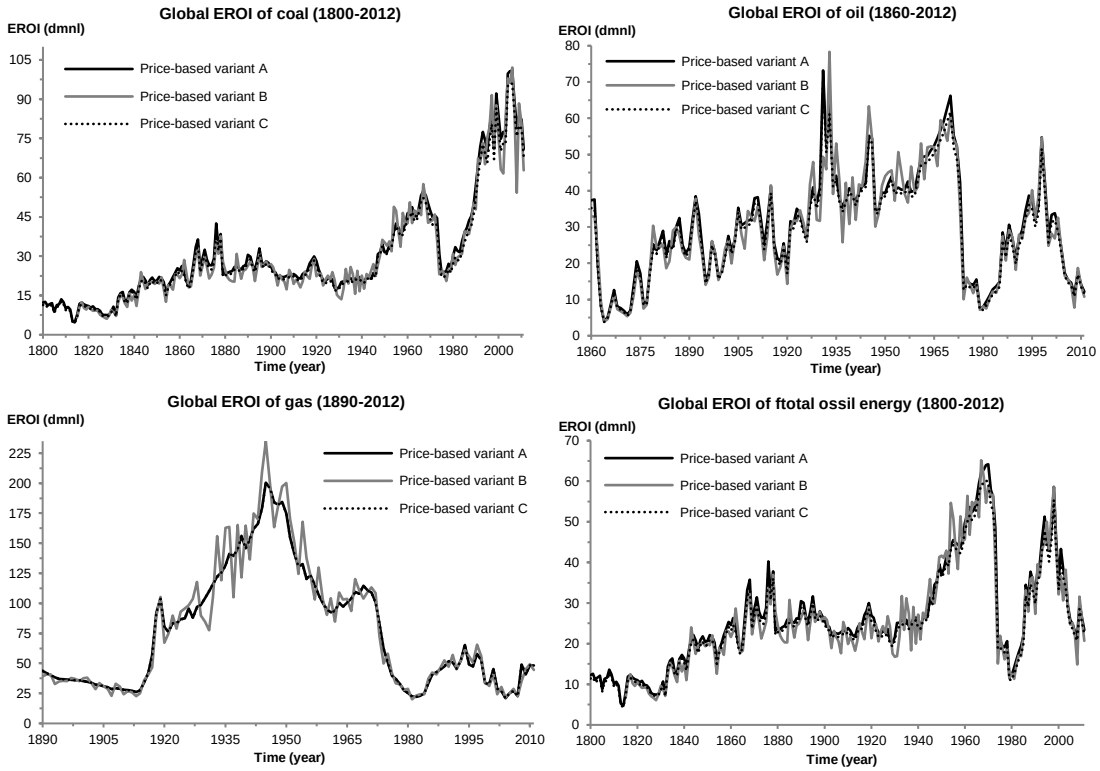


Figure 14. Comparison of variants A, B, and C, for estimating the global EROI of coal, oil, gas and total fossil energy.

Sensitivity of price-based results to the energy intensity

It is very likely that the different expenditures of the global fossil energy sector present overall a higher energy intensity than the average expenditures of the global economy. Indeed, the share of energy-intensive capital components such as steel is higher in the energy sector than in the global economy which relatively relies on more services (with less embodied energy). 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 should logically have overestimated the different EROI that we have computed through our price-based methodology. This choice was made in order to have a time-dependent energy intensity, and Figure 5 shows that indeed the energy intensity of the global economy has substantially decreased from 1800 (30 MJ/$1990) to 2012 (10 MJ/$1990). In their study concerning the EROI of US oil and gas production, Guilford et al. (2011) also used a national average of the energy intensity (8.3 MJ/$2005, i.e. 12.4 MJ/$1990), but they have then tested the sensitivity of their results with two other values: an estimate of the energy intensity of the US oil & gas industry expenditures of 14 MJ/$2005 (i.e. 20.92 MJ/$1990) based on the data of the Green

Design Institute of Carnegie-Mellon University, and an arbitrary high estimate of 20 MJ/$2005 (i.e. 29.9 MJ/$1990). In Figure 15 we show the effect of using energy intensities of expenditures equal to 150% and 200% of the global economy average on our price-based estimates of the global EROI of crude oil from 1860 to 2012. As previously anticipated, using the global energy intensity average tends to imply an overestimation of the resulting EROI. Nevertheless, the broad trend of the global EROI of crude oil is conserved and that is also true for coal and gas, so we can be confident in our main results: maximum global EROI seems to have been reached in the past for crude oil and gas, whereas increasing net energy yields are still to come for coal global production.

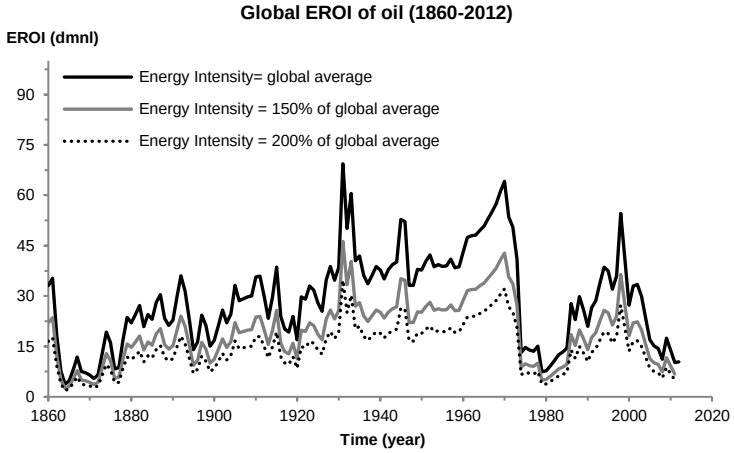


Figure 15. Sensitivity of the global EROI of crude oil to the energy intensity, 1860–2012.

4.2 Comparison of price-based results with existing studies

To check the robustness of our price-based estimates 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 presented from 1992 to 2006. Hence, using our price-based method, we built an estimate of the global EROI of the joint oil and gas production (based on relative quantities of production) and compared it to the one of Gagnon et al. (2009) in Figure 16. Overall, all our estimates 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 mostly comes from the irreducible volatility of energy prices we used, and the fact that we use a time-dependent energy intensity whereas in Gagnon et al. (2009) this variable is constant and worth 20 MJ/$2005.

If we had computed the global EROI of combined oil and gas productions with an energy intensity 150% higher than the global economy average, whatever the MROI variant, results would have been much more in line with Gagnon et al. (2009). 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 $EROI_A$ overestimate the one of Gagnon et al. (2009) by 20%. 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 US coal EROI of Cleveland (2005).

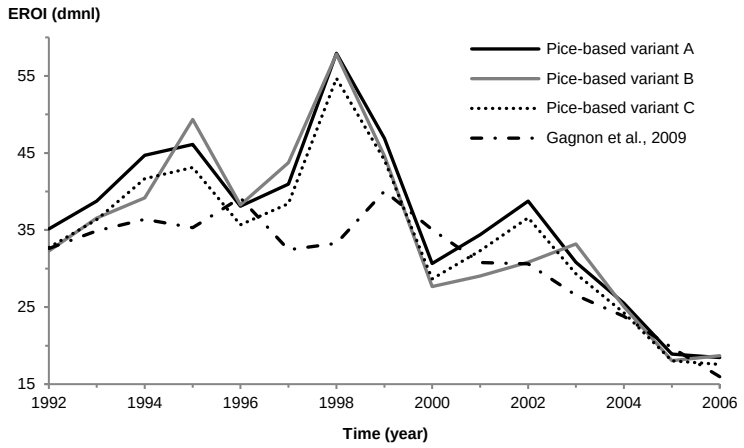


Figure 16. Comparison of price-based global EROI of oil and gas with the one of Gagnon et al. (2009), 1992–2006.

4.3 Sensitivity of EROI theoretical models to the URR

Given the potentially highly controversial aspect of the prospective results delivered by the theoretical EROI models, sensitivity analysis needs be carried out. The key parameter of both ("modified Dale et al., 2011" and "new") theoretical EROI models is the value retained for the URR. Let us first notice that, as can be seen in Figure 17 (up) 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 & Evans, 2009) instead of the previous 105 000 EJ hypothesis, does not change the estimations of the past theoretical EROI from 1800 to 2012. This is because the curve-fitting procedure (minimization of root square errors sum) generates 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 17, down left) that has consequently a different prospective evolution (still approached by a sigmoid increasing function). Finally (Figure 17, down right), 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, 2015 instead of 2023, and at a lower value, 93:1 instead of 101:1. Nevertheless, considering that this sensitivity analysis has consisted in a three-fold division of the coal URR estimation, these results can be considered as quite robust.

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 only changes the slope of their future respective decreasing EROI, but under no circumstances could it generates a new EROI peak. 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 production of unconventional fuels are really scarce. Yet, given the increasing prevalence of unconventional fossil fuels in the primary energy mix, it will be needed to perform again the analyses of the present paper in a few decades. This could show that even if it is certain that maximum EROIs have already been reached for conventional fossil fuels, it might not be the case for their unconventional means of production. Indeed, the future preponderance of unconventional fossil fuels production will enable a clear distinction between conventional and unconventional fossil fuel EROIs, which will be of great interest since EROI gains in unconventional production are expected by many whereas our results seems to indicate that the time of increasing EROI has long past for conventional oil and gas production.

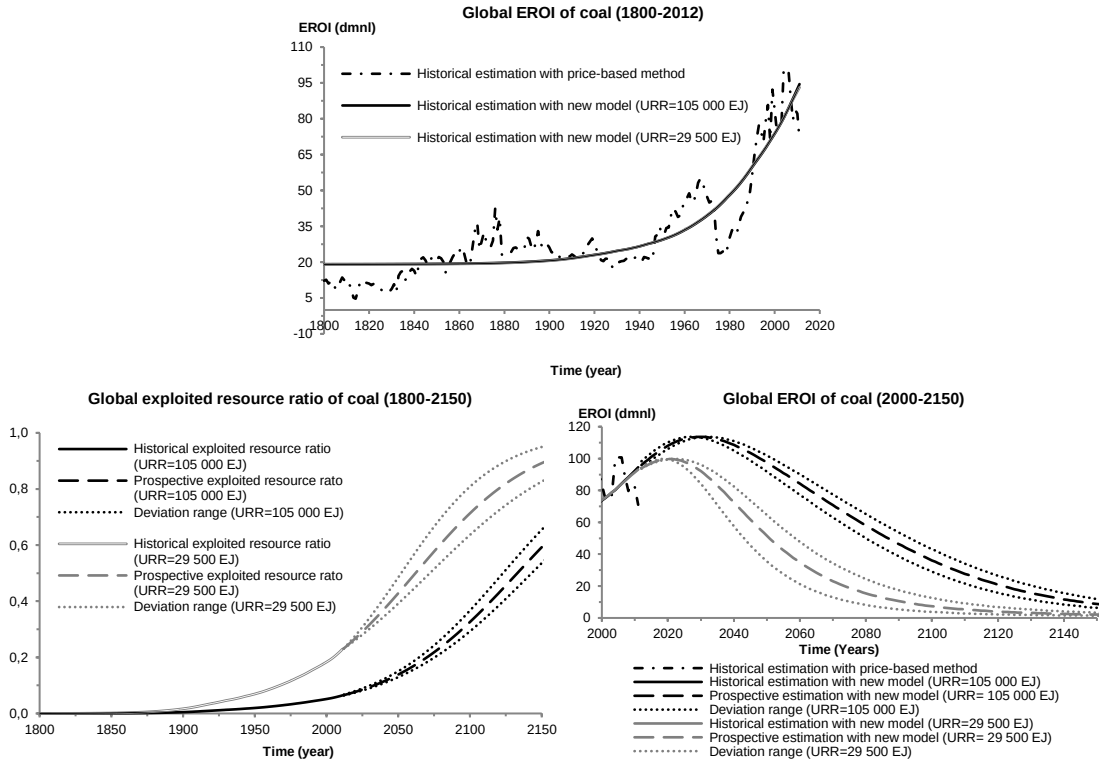


Figure 17. Sensitivity analysis of the "new" theoretical EROI model in the case of coal, using the 29 500 EJ URR estimation of Mohr & Evans (2009) instead of the 105 000 EJ estimate of McGlade & Ekins (2015).

5. Conclusion and perspectives

So far historical EROI trends had been estimated for a few decades at most. Consequently, the hypothesis that maximum EROI of fossil fuels had already been reached long ago had been advanced several times without any real verification. In order to address this problem we have first relied on a price-based approach. By collecting and harmonizing several types of data, we have provided a very long term historical perspective of (constant $1990) fossil energy prices per same energy unit (TJ)[12]. This has allowed us to estimate the quantity-weighted average price of aggregated fossil energy from 1800 to 2012. Then, thanks to three variant MROI estimates that proved to deliver very consistent results, we have estimated the global EROI of coal, oil, and gas from the beginning of their production (1800, 1860, and 1890 respectively) to 2012, which furthermore allowed us to compute an EROI for the global primary fossil energy sector from 1800 to 2012. 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 consistency with Cleveland (2005) was also found for what could be considered as the current (i.e. beginning of twentieth century) EROI of coal. Our price-based estimates of global historical fossil fuels EROIs have shown that maximum EROIs were reached in the 1930s–40s for oil and gas, respectively around 50:1 and 150:1, whereas the maximum EROI of global coal is still to

12 The tremendous work of Fouquet (2008) offers an even more precise historical perspective on energy prices with however a geographical perimeter restricted to the UK and a focus on energy services and not primary energy.

come. We have then confirmed these historical price-based 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. Of course, the two theoretical models that we have tested gave much more smoothed trends compared to the price-based method, but overall we observe a good concordance between the two approaches and, as already said, with more empirical analyses such as Gagnon et al. (2009) and Cleveland (2005). This comparison indicates that "real" physical past EROIs are somewhere between the extra-smooth estimate of theoretical models and the more volatile price-based estimations. The EROI theoretical models also allowed us to perform some prospective estimates of future fossil fuels EROI. This work is especially interesting regarding coal since its maximum EROI has not yet been reached. Simulations have showed discrepancies among models and URR hypotheses 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 between 2020 and 2045, around a value of around 95(±15):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 largest part of the renewable energy supply at global level by providing an important share of the energy supply of 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 electricity ensures a growing share of global final energy consumption, we think that future researches should also focus on estimating long-term trends in final and not primary EROI. Finally, as we have based our work only a global view of the economy, 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.

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