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# Modeling and communicating the dynamics of energy market

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*Calculemus!*

Gottfried Wilhelm von Leibniz
(Lipsia, 1646 - Hannover, 1716)

*Non exiguum temporis habemus, sed multum perdidimus.*

Lucio Anneo Seneca, *De brevitate vitae*, 1, 3
(Cordova, 4 a. C. - Roma, 65)

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# Introduction

The aim of this research is the investigation of the analogies between the dynamics of oil production, the economy and the physical laws that are related to every natural process. The difficulty to retrieve data concerning the oil market suggests a possible analogy with what happens in the field of Science Communication: indeed, while in the magazines many articles can be found about climate change, for instance (figure 1), we seldom see articles on related topics with keywords such as "energy resources" or "energy depletion"[1].

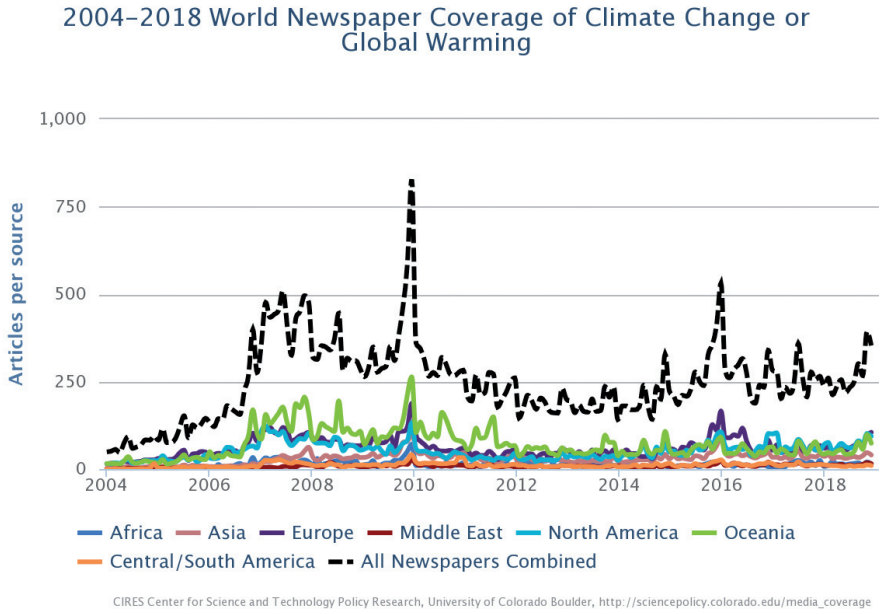



**Figure 1:** *Picture elaborated by Boykoff, M., Daly, M., Fernández-Reyes, R., McAllister, L., McNatt, M., Nacu-Schmidt, A., Oonk, D., and Pearman, O. (2018) – see bibliography.*

[1] Could be useful using Google trends page to look at the frequency related to two or more terms like, for example, "climate change", "energy depletion", "peak oil" and so on. The number of research for the first is greater than the others and – matched to "energy depletion" – the latter seems to be almost zero.

Therefore, trying to fill the gap between public communication and the real data used by science, the effort was focused on discovering "where we are" about the energy. In particular, with this special form of energy (oil and gas) that powers the World economy and was the main instrument to impress a great development to our society – after World War II and in the First World especially.

The weight of energy in society is given by the first two pictures in Chapter 2. These pictures show the global energy consumption (expressed in EJ) and population growth. Many researchers have stressed this point: without energy, there has been no social and cultural development from a historical point of view.

In particular, the Anthropocene[2], the era in which humans have the most powerful influence on global ecology, is started since the mid-twentieth century (following some authors[3]). The accelerating pace of energy use, greenhouse gas emissions, and population growth have thrust the planet into "a massive uncontrolled experiment". In particular, there is (1) a direct correlation between energy availability and population growth and (2) the growth of energy per capita along the last two centuries, despite the population growth has an exponential trend. In this situation, the role of energy systems is predominant: that is why my research started with the investigation of the EROI for the oil companies (Chapter 1) and, later, tried to model the economy of oil (Chapter 2).

One of the most commonly used – even if controversial[4] – index to measure the quality of an energy resource is the EROI (acronym for *Energy Return on Investment*). The knowledge of this parameter in traditional energy resource (oil, gas) allows us to have an idea about the state of production, consumption, depletion etc. in this strategic sector and it is, in any case, fundamental as an index of the energy quality used by the society. This is the reason why the EROI is crucial to determine the convenience of an energy resource in general and particularly for oil and gas, that nowadays satisfy about 57% of primary energy demand worldwide[5].

[2] The term was popularized by Paul J. Crutzen, Nobel prize winner in 1995 for Chemistry, in a series of publication: Crutzen P. J., Eugene F. Stoermer E. F. (2000); Crutzen P. J. (2005); Zalasiewicz J., Williams M., Steffen W., Crutzen P. J. (2010); Steffen W., Grinevald J., Crutzen P. J., McNeill J. (2011). "The Anthropocene: conceptual and historical perspectives". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 369 (1938): 842–867.

[3] McNeill J.R., Engelke P. (2016).

[4] A few years ago, I have subscribed to the Energy Transition list – a group of experts, academics and people directly involved in the energy sector – moderated by prof. Ugo Bardi. Between the end of 2016 and all 2017, with a typical frequency of all mailing lists (some calm periods, alternate to "outbursts") the discussion topic was still a correct definition of the EROI and what should be the boundaries inside which to stay for a correct calculation of the index. This issue was discussed also in Hall C. A. S., Lambert J. G., Balogh S. B. (2014).

[5] BP Energy Outlook data, 2016. The percentage grows up to 85% if we consider coal.

This dimensionless index is generally defined as the ratio between the energy extracted from a given resource and the energy costs sustained to get that energy.

Researchers have developed different methods to calculate the EROI values. In many cases, most of them provide precise values but they are measured on specific sites (single oil fields or limited regions). For example, Brand-Correa et al.[6] have developed an Input-Output based methodology to calculate a national-level EROI ($EROI_{nat}$). They start with a succinct background of the EROI concept and its different types. Then they go ahead by putting forward some arguments on the conceptual relevance of an $EROI_{nat}$ and discuss frequent conceptual issues in the EROI literature, describing the conceptual choices they made.

In order to better understand the drivers of the energy productivity in oil production sector, Brandt et al.[7] use an approach that applies a detailed field-level engineering model of oil and gas production to estimate energy requirements of drilling, producing, processing, and transporting crude oil. They examine 40 global oilfields, by using detailed data for each field from hundreds of technical and scientific data sources.

Few authors[8] tried to assess the worldwide values of EROI for global oil and gas production, even if the data present in this work begin to age.

Only in one of these works[9], it has been possible to find general, more recent data, valid worldwide and with historical perspective, even if with a not convincing general method: the use of the MROI (Monetary Return on Investment) as a reliable proxy to calculate the EROI.

The use of MROI is not convincing because it introduces an economical parameter as an indirect way to estimate the quality of an energy resource and money obeys laws quite different from those of Physics or Thermodynamics[10].

Despite the difficulties to retrieve data from oil companies[11], the aim of this research is trying to find a general method, valid for most cases – obviously in presence of appropriate, useful data.

Therefore, Chapter 1 describes the attempt to set up an alternative method for the calculation of the EROI of oil companies. The difficulties to retrieve the data from the oil companies are notorious, thus the strategy consisted in using a proxy of the energy

[6] Brand-Correa L. I., Brockway E. P., Copeland C. L., Foxon T. J., Owen A., Taylor P. G. (2017).

[7] Brandt A.R., Englander J., Bharadwaj S. (2013); Brandt A.R., Sun Y., Bharadwaj S., Livingston D., Tan E., Gordon D. (2015).

[8] Gagnon N., Hall C. A. S., Brinker L. (2009).

[9] Court, Fizaine (2017), discussed in the following sections.

[10] A part of this project is focused on the attempt to shape the oil market as a natural phenomenon and it is discussed in Chapter 2.

[11] The energy is usually a strategic sector for a country. The oil companies, public or private and even if multinational, do not release sensitive data on resources exploitation.

costs, i.e. the available data about the $CO_2$ emissions of the same oil companies, as reported in their own sustainability reports (SRs). International organizations such as IPCC and WBCSD recommend to the involved companies to compile these reports, but they are not mandatory. The second step was to use, as a proxy of the energy extracted, the $CO_2$ emissions estimate obtained by an appropriate stoichiometric conversion of the oil production declared by the oil companies.

The resulting estimates of EROI are rather homogeneous and not too different from the values reported in the literature[12]. The method could be suitable for year-by-year comparison of the time evolution of this important energy quality parameter for the individual energy-producing and energy-delivering companies[13]. Such a parameter has been defined as the "corporate's EROI" and denoted with $CO_2$ROI.

In particular, this work encountered its main hurdle collecting the data to make comparisons among the different oil companies. As mentioned above, this is also reflected in the communication sector and it is discussed in details in Chapter 3.

In order to shed light on the global energy landscape (in Chapter 2), the research was focused on the price vs production trajectory investigation (that was named phase-plot) of worldwide oil production in the 1965-2014 time domain. The idea was that the laws governing the convective intensity and the oil production on one side, and the energy flow in human society on the other, were similar. In particular, this analogy could be true for the change from a slow diffusion process to a faster convective movement, following thermodynamics laws. This suggestion can be strange but there is a literature on this, for example, for the social structure[14], for the market economy[15], without forgetting the evolutionary dimension[16].

As a first approximation, the attempt is to describe theoretically the phase-plot system: the starting point is to imagine the system without perturbations with a worldwide average EROI that varies from 60 (1965) to 15 (2014). Similarly, it is picked up the value of world production in 1965 (1,567 Million ton/years) and in 2014 (4,220 Million ton/years), assuming a constant increment of the production. Obviously, the phase-plot describes the evolution of the real system and appropriately shows two evident "loops" in correspondence of the two major oil crises in recent times (in the '70s of the last century and in the '10s of the current century), although it is also apparent a "background" (or floor) price the system has never overcome. We called this theoretical curve "background" or "floor".

[12] Some of them are cited in the previous footnotes and, in addition, is useful see the bibliography and the followings reference: Guilford M. C., Hall C. A. S., O'Connor P., Cleveland C. J. (2011); Gupta A., Hall C. A. S. (2011).

[13] Celi L., Della Volpe C., Siboni S., Pardi L. (2018).

[14] Bejan A., Gunes U., Errera M. R., Sahin B. (2018).

[15] Gumjudpai B. (2018).

[16] Roddier F. (2016).

Following the idea of a possible description of the global oil market trend as a dynamical system, the investigation was focused on the possible analogies between the time behavior of the oil market and a classical dynamical system, which is well known to exhibit an almost doubly cyclic behavior, i.e., the Lorenz attractor.

However, this speculation remained nothing better than that, because the major drawback of this idea is the difficulty to conceive that only two loops in a phase-plot could be assimilated *tout court* to a Lorenz attractor: the investigated period 1965-2014 is in fact too short to validate such an analogy. Therefore, the output of this branch of the research was deposited in the arXiv online repository[17].

The relationship between natural phenomena and price-production dynamics of oil extraction, however, could be seen from another point of view. Indeed, the phase-plot, behind the "erratic behavior" initially regarded as a clue of a Lorenz attractor, highlighted the occurrence of two peaks in correspondence with the upper part of those loops. This "swinging" (macro)behavior is rather similar to that of a very rough theoretical model where we only have two stocks of oil and two prices for them. The first delimited by a price of 100 $/barrel, for a production that remains between 0 and 1,000 barrels/day; the second with a cost of 200 $ for a production in the range 1,000-1,500 barrels/day[18]. In this ideal case, following the consumption, we expect the same swinging behavior: if the consumption is in the range between 0 and 1,000 barrels/day, the oil at the lower price will be only used, with a price (ideally) of 100 $/barrel. Since consumption generally grows, the economic system reaches a point in which it needs to use the second stock of oil at the higher price. As the oil is a global commodity, the price of all oil is determined by the marginal oil barrel, that is to say by the most expensive one (200$). In this ideal dynamics, the price suddenly jumps to the higher level instead of slowly shifting up. If the oil price increases, however, the consumption decreases and, sooner or later, the society comes back to the previous range of extraction intensity. The main characteristic of the simple oil-price dynamics described here is that there are two rapid movements on the cycle (rise and descent of the price) and two slow movements (consumption that goes up and down, to adapt to the oil price). At this level it could be useful thinking of the dynamics in terms of EROI instead of oil stocks (with high and low prices). Therefore, natural variables seem to be more similar to mean price and mean EROI (fast the former, slow the latter).

Oscillating behavior actually indicates only a qualitative dynamics, a thought pattern, but there are known formalizations of such a kind of behavior, like those described by Lotka-Volterra equations. This is a possible way to get a dynamic model, although very simple. The Lotka-Volterra model was successfully applied to the description of

[17] https://arxiv.org/abs/1708.03533

[18] These numbers are not real and are used just for the example.

many processes occurring in nature. One of them seems to have the same features of the simple oil market behavior just described. More specifically, the analogy is between a prey, the American spruce, and a predator, the caterpillars of the species *Choristoneura fumiferana* that feed on the spruce. The caterpillar population is regarded as the fast variable, since there are periodically observed demographic outbreaks of this species, considered a real scourge[19], whereas the spruce leaf whole surface is assumed to be the slow variable because the regeneration of the leaves – and not only – is a process that lasts several decades.

To test the spruce-budworm model, it was also implemented in Vensim, a software used in the System Dynamics modelization, moving from differential equations to a useful model to make predictions or to be integrated into a larger model.

The fil rouge that leads the structure of this Ph.D. project is the research of some experimental results like the estimation of the EROI for the oil companies (Chapter 1) and the integration of these results with a background scenario described as a theoretical structure where, in general, it is possible to show the behavior of the oil market dynamics (Chapter 2), finally represented as a natural/ecological system.

At the end (Chapter 3), the communication issue is recalled. As already mentioned, if we make a research by using, e.g., Google Trends with keywords like "climate change", "energy resource" and "energy depletion", we can easily see that while the first one has a certain number of hits, the latter are, more or less, close to zero. I am personally committed to filling the gap (thanks to my previous background in Science Communication), to sensitize the citizenship to the energy transition problem. That is why last year, at the Bright event (European Researchers' Night), I have developed a game about the Hubbert's peak oil to play with people and explain to them the dynamics of peak and resource depletion.

[19] Celi L., Della Volpe C., Siboni S., Pardi L., *Spruce budworm and oil price: a biophysical analogy*, ISBPE (International Society for BioPhysical Economics) 2018 Conference: «Developing Economics for a resource constrained world», June 13th-17th, Wells College, Aurora, NY, USA.

# Chapter 1.
# A new approach to calculating the "corporate" EROI

## 1. Introduction

The present time energy conundrum needs to be rationally unraveled by quantitatively comparing the various available primary energy sources. Most energy analysts consider the EROI, acronym for Energy Return On (Energy) Investment, as the best tool to estimate the quality of the energy sources of a society[1]. Although a number of different Energy Return Ratios have been defined[2], the simplest choice is to calculate the ratio between the energy delivered to the society by the producers and the energy employed to get that amount of energy[3]. For the simplest form of human society, that of hunters-gatherers, the aggregate EROI is given by the sum of the individual returns of the members of the society, suitably corrected by the effects of cooperation. Not much differently, the EROI of industrialized societies can be seen as the sum of the EROI of the different energy producers corrected by the effects of cooperation and competition. If this is true, it would be vital to estimate the EROI of the individual energy producing companies and, in particular, that of the petroleum companies, since today oil and gas globally provide more than 50% of primary energy consumption, and because oil and gas, as finite resources, are expected to show a time declining EROI.

[1] Hall C. A. S. (2017); Fizaine F., Court V. (2016); Court V., Fizaine F. (2017); Cottrell F. (1953); Gagnon N., Hall C. A. S., Brinker L. (2009); Gupta A., Hall C. A. S. (2011); Hall C. A. S., Powers R., Schoenberg W. (2008).

[2] Brandt A.R., Dale M. (2011); Brandt A.R., Dale M, Barnhart C. (2013); Cleveland C.J. (2006-1); Cleveland C.J. (2006-2); Murphy D.J., Hall C.A.S., Cleveland C.J. (2011); Mulder K., Hagens N.J. (2009); Guilford M.C., Hall C.A.S., O'Connor P., Cleveland C.J. (2011); Cleveland C.J. (1992); Cleveland C.J. (2005); Brandt A.R., Sun Y., Bharadwaj S., Livingston D., Tan E., Gordon D. (2015); Brandt A.R., Englander J., Bharadwaj S. (2013).

[3] Hall C. A. S., Klitgaard K. (2011).

Usually EROI is simply defined as:

$$EROI = \frac{Energy\ extracted}{Energy\ costs} \qquad \text{[eq. 1.1]}$$

In spite of the simplicity of the concept, many difficulties arise in calculating meaningful values of EROI for different sources of primary energy and set up a sensible comparison among the EROI of the different energy technologies[4]. One of the main problems is the definition of the boundaries within which the calculation and the comparisons are performed[5]. Moreover, there are at least two methodological choices, that can be referred to as a bottom-up or a top-down approach. In the first one, the engineering details of the energy technology and the full Life Cycle Analysis of the technology are analyzed starting from the detailed knowledge of the plants extracting energy from natural sources and fluxes[6]. In the second one, energy costs and revenues are estimated by some general approach based on the final price of energy[7]. In the case of oil and gas, for instance, the EROI can be calculated starting by the estimate of the actual energy costs of drilling, development and completion of petroleum rigs[8] or functionally linking the value of the EROI to the market global price of the commodity (oil, gas or coal)[9].

The boundaries of the fossil fuels energy supply chain are outlined in the scheme of Figure 1[10].

The energy losses along the chain, and the consumption of energy delivered by further blocks in the scheme, determine the net energy finally delivered to the society, which in turn gives a measure of the societal well-being[11]. In a market economy, the energy is supplied by the energy industry (Figure 2), which is the social entity sustaining the energy costs that enter in the EROI calculation. A number of big and medium firms supplying different goods and services makes up the energy industry.

[4] Hall C. A. S., Lambert J. G., Balogh S. B. (2014).

[5] Murphy D. J., Hall, C. A. S. (2010).

[6] Brandt A.R., Yeskoo T., Vafi K. (2015); Raugei M., Leccisi E., Azzopardi B., Jones C., Gilbert P., Zhang L., Zhou Y., Mander S., Mancarella P. (2018); Raugei M., Sgouridis S., Murphy D., Fthenakis V., Frischknecht R., Breyer C., Bardi U., Barnhart C., Buckley A., Carbajales-Dale M., Csala D., de Wild-Scholten M., Heath G., Jæger-Waldaup A., Jones C., Keller A., Leccisi E. , Mancarella P., Pearsall N., Siegel A., Sinke W., Stolz P. (2017); Zhou Z., Carbajales-Dale M. (2018).

[7] Court V., Fizaine F. (2017).

[8] Brandt A. R., Yeskoo T., Vafi K. (2015); Carmalt S. W. (2017).

[9] Court V., Fizaine F. (2017).

[10] Murphy D. J., Hall C. A. S., Cleveland C. J. (2011).

[11] Hall C. A. S., Klitgaard K. (2011); Hall C. A. S., Lambert J. G., Balogh S. B. (2014).

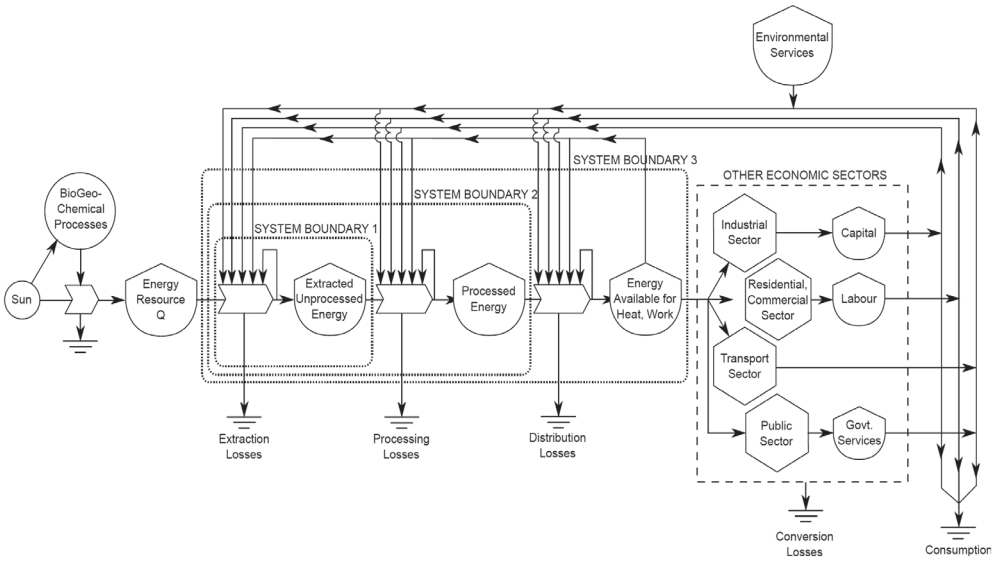



**Figure 1:** *The energy system is depicted as a series of stages: extraction, processing and distribution. The economy is split into four sectors: industrial, residential, transport and public, with associated outputs.*

A relatively small number of international corporations involved in petroleum business covers the whole supply chain, from prospection and extraction to distribution of petroleum products, i.e. from up to downstream. Evaluating the energy costs along the supply chain of petroleum products for these corporations could be a method to estimate the societal EROI of petroleum products and its time evolution.

We propose to address this problem by using the Sustainability Reports (SRs) of oil companies and define the result of these evaluations as the Corporate EROI, or $EROI_{INC}$. This is essentially a measure of the net energy delivered to the society by each single considered corporation (see Figure 2), that is to say a component of the societal EROI defined by Hall, Lambert and Balogh[12].

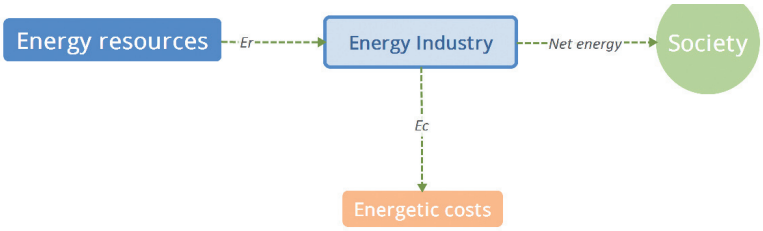



**Figure 2:** *The schematic way to represent the EROI, with Er = Energy return and Ec = energetic costs.*

[12] Hall C. A. S., Lambert J. G., Balogh S. B. (2014).

The SRs report the total emissions of the company and we directly correlate this datum with the energy costs[13]. The energy produced is given by the petroleum quantity extracted by each company found in their annual reports. The EROI is then calculated as a ratio whose numerator is given by the amount of $CO_2$ corresponding to the oil and/or gas produced by the company, as shown in section 3, and the denominator by the $CO_2$ emissions declared by the company in the SR. In other words, the $CO_2$ quantity at the numerator is a proxy of the energy produced while the $CO_2$ amount at the denominator is a proxy of the energy consumed along the whole production and delivery chain. The expression of the corporate EROI, becomes therefore:

$$EROI_{INC} = \frac{[CO_2]_{prd}}{[CO_2]_{emiss}} \qquad \text{[eq. 1.2]}$$

where $[CO_2]_{prd}$ is the oil production in $CO_2$ equivalent and $[CO_2]_{emiss}$ denotes the $CO_2$ emissions as found in the SR of the considered corporation.

It may appear strange to introduce a $CO_2$-based metric to estimate the EROI. However, one should consider that in a sense such an approach is very similar to use a money-based metric like the Monetary Return on Investment (MROI), a market based-metric that may be related to the EROI through an appropriate energy intensity factor, as discussed in Court V., Fizaine F. (2017). Although it sometimes forces to a significant approximation, this metric is commonly accepted and its accountability has been proven.

Even if this approach, in the end, has not really convinced me because using the monetary proxy is a way to insert another variable, independent by the physics and thermodynamics laws. This long citation can clarify my words:

> The contrast between Canadian and Japanese energy use points to another important issue: efficiency. At the end of the twentieth century, Japan required about a third of the energy needed to produce a dollar's worth of GDP, compared with Canada. European economies were almost as efficient as Japan. At the other extreme were rapidly industrializing countries, including China and India, whose economies were five to six times less efficient than Japan and two to three times less efficient than Canada and the United States. Such figures underscore two distinctions. First, the energy efficiency of national economics has tended to follow a historical pattern. The typical economy's energy use per GDP (energy intensity) rose quickly as it entered a period of rapid and heavy industrialization. This spike in energy intensity would normally be followed by a long and gradual decline as the economy began to use energy more efficiently. This was the his-

[13] Each oil company draws up its SR and, where available, this document can be found on the website of the oil company itself. In appendix 2, we leave a foot-page note with the web addresses where we have found the SR, for each oil company examined.

> torical experience of Great Britain, which peaked in the 1850s, Canada (peaked around 1910), and the United States (peaked around 1920). Not all economies have functioned in this fashion, however. Japan's economy maintained stable but comparatively low energy intensity throughout much of the twentieth century. Second, significant efficiency variations within the rich world showed that it was possible to become wealthy using energy at much lower levels than did Canada and the United States. There were many factors that explained why national economies in the rich world diverged, ranging from industrial mix to regional climate to suburbanization patterns. Comparative data showed that core quality-of-life indicators (including infant mortality, life expectancy, and food availability) did not improve substantially beyond annual energy consumption levels of roughly one-third to one-quarter those of the United States and Canada.[14]

Our proposal makes use of another kind of metric, for which it is necessary to develop a specific correction, due to the different energy release of produced $CO_2$. We will show that this can be done in an acceptable way, even if with a certain approximation, as illustrated in Section 5.

## 2. The Sustainability Reports

Oil companies are required to draw up a SR every year, in response to the growing concern – of media, public opinion, international institutions etc. – about the climate change and environmental impact of humankind in general[15]. These reports are strongly recommended by international institutions, although not mandatory.

To this purpose, the World Resources Institute (WRI) and the Worlds Business Council for Sustainable Development (WBCSD) have created the Greenhouse Gas Protocol Corporate and Accounting Standard (GGPCAS)[16]. The GGPCAS helps industries and oil companies to measure, manage and reduce emissions of the main Green House Gases (GHGs): $CO_2$, $CH_4$, $N_2O$, HFC, PFC, and $SF_6$.

The starting point of this procedure is the observation that the industrial activities of an oil company go beyond the boundaries of the company itself. The goal is to show that the sustainable development could be economically convenient, with the definition of common instruments and shared standards to quantify the GHGs emissions. These instruments – defined by GHG Protocol Corporate Standard – are coherent with the IPCC standards for the calculation of the $CO_2$ emissions on a national basis[17].

This protocol classifies three distinct components of the company's emissions: the Scope 1 is focused on direct emissions, which are related to resources under the prop-

[14] McNeill J.R., Engelke P. (2016), pp. 133-134.
[15] GHGPT (2011).
[16] GHGPT (2011).
[17] GHGPT (2011).

erty of the company or under its control, while the Scopes 2 and 3 are focused on indirect emissions, i.e. related to resources not directly controlled by the company.

The companies that subscribe the protocol should provide the emissions referred to Scope 1 and 2, but there is more flexibility about Scope 3.

With respect to Scopes 1 and 2, Scope 3 expands the analysis of the emissions, considering, besides the direct activities, the indirect ones (acquisition and refining of materials, storage, distribution, use and end- of-life of products, etc.). The aim of this standard is to estimate the time evolution of the GHG emissions of a single company. The activities concerning Scope 3 are subdivided into 15 items that go from purchasing goods and services, to the downstream activities like the transportation and distribution of products sold by the reporting company[18].

Drawing up a report that takes into account the indications drawn by the Scopes, a company can give a complete framework on its own environmental impact in terms of GHG emissions. The indirect emissions indicated in the Scope 2 and 3 are clearly defined in the protocol:

- the Scope 2 considers the emissions caused by the use of electricity, cooling, and heating;
- the Scope 3 takes into account the emissions generated inside the production chain: upstream (the job before the actual job of the company, like the acquisition of goods and services) and downstream (for the section of the production chain that follows: selling of goods and services).

The protocol identifies – in the principles of significance, completeness, accuracy, coherence, and transparency – the guidelines to follow in order to avoid the omission of activities that could compromise the reliability of the reports. The most important activities are those who have major emissions and therefore the largest opportunities of reduction.

## 3. The calculation method

Here we propose a simple way to calculate the $EROI_{INC}$ via the $CO_2$ volumes. First, we calculate the ideal volume of $CO_2$ relative to the production of oil by the company, which will be the numerator of our energy return ratio. To do this calculation we note that the basic oxidation reaction that produces the carbon dioxide when burning fossil fuels is:

[18] For a complete list of the activities pertaining to Scope 3, and for a general overview about the Scope identification and goals, see GHGPT (2011) – for detailed list pp. 34-37.

$$-CH_2- + \frac{3}{2} O_2 \rightarrow CO_2 + H_2O \qquad \text{[eq. 1.3]}$$

For the sake of simplicity, we further assume that oil is nothing else than a collection of (-$CH_2$-) molecular units, i.e. that the main contribution to $CO_2$ production comes from oxidation of (-$CH_2$-) monomers, while that due to other sources (-$CH_3$ groups, aromatic units, etc.) provides only a minor correction to the whole $CO_2$ production. Therefore multiplying the weight of the yearly oil production of a company by the ratio between the molecular weights (MW) of $CO_2$ and -$CH_2$-, i.e.:

$$\frac{MW_{CO2}}{MW_{-CH2-}} = \frac{43.99}{14.03} = 3.14 \qquad \text{[eq. 1.4]}$$

we obtain the $CO_2$ quantity corresponding to the production. This number will provide the numerator of the $EROI_{INC}$ in equation 1.2. For the conversion between barrels of oil and the corresponding weight in kg, it is necessary to know the oil density rho ($\rho$).

For this purpose we take the average worldwide value[19] of $\rho$ = 863.6 kg/m$^3$. These assumptions correspond to take the oil commodity as a globally homogeneous chemical mixture with the same composition and properties, that is to say containing the same mixture of hydrocarbons. This approximation is coherent with the generally accepted use of international statistics about oil, to report the sum of the volumes of the different oil categories (crude and condensate, NGL, light tight oil, etc.) and, for our purpose, gas. Indeed, the amount of gas production is directly derived using SRs or/and Annual Reports (ARs) as a source of data and often there is a lack of differentiation between oil and gas about the production data.

What we have found in SRs, subdividing oil and gas is a prevalence of oil production (67% the total amount for analyzed companies) than gas (33%) , to be compared to the BP Statistical Report that, for the whole hydrocarbon production worldwide, estimate the division between the 59% of oil production and the 41% gas. Therefore this appears a significant approximation, but it is, in a sense, intrinsic and unavoidable for the chosen method and for the kind of EROI, the corporate EROI. Notwithstanding this approximation we will see in section 6 that the final weighted result for all the corporate EROI considered in the present paper (87% of world oil production) is not far from the commonly proposed value for the global oil production.

[19] For the method of calculation, see the Appendix 1.

### *3.1 A case study: the Shell Sustainability Report*

Among the available SRs one of the clearest and most compliant with the Scope 3 indications is the Shell report[20], that we use here as an illustrative example.

The Shell oil production in 2015 was 3 x $10^6$ [barrels/day][21], thus corresponding to a total oil mass of:

$$M_{oil} = 3 \times 10^6 \left[\frac{barrels}{day}\right] \times 365 \left[\frac{days}{year}\right] \times 0.1589 \left[\frac{m^3}{barrel}\right] \times 863.6 \left[\frac{kg}{m^3}\right] =$$

$$= 150.26 \times 10^9 \left[\frac{kg}{year}\right]$$

Such a yearly production is equivalent to a value of $CO_2$ (directly emitted) given by equation 1.3, i.e.:

$$M_{CO2} = 150.26 \times 10^9 \left[\frac{kg}{year}\right] \times 3.14 = 471.81 \times 10^6 \left[\frac{tons}{year}\right]$$

From the Shell SR we retrieve the value of the direct emissions equal to 72 million tons of $CO_2$ equivalent per year (2015)[22]; the value of $EROI_{shell}$ is therefore:

$$EROI_{shell} = \frac{471.81 \times 10^6 \left[\frac{tons}{year}\right]}{72 \times 10^6 \left[\frac{tons}{year}\right]} = 6.55$$

One simpler way – even if less accurate – to write this equivalence is to use the coefficient 0.43, found on the website https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (it is necessary to scroll the page until the voice "Barrels of oil consumed"). In this case the calculation is:

$M_{oil} = 3 \times 10^6 \times 365 \times 0.43 = 470.85 \times 10^6$ [tons/year] and the EROI will be:

EROI = $(470.85 \times 10^6) / (72 \times 10^6) = 6.54$.

In any case, if allowance is made also for indirect emissions, we have:

$$EROI_{shell} = \frac{471.81 \times 10^6 \left[\frac{tons}{year}\right]}{81 \times 10^6 \left[\frac{tons}{year}\right]} = 5.82$$

[20] Shell Annual Report and Form 20-F 2015. Available online at: http://reports.shell.com/annual-report/2015/servicepages/downloads/files/entire_shell_ar15.pdf

[21] Ibid, p. 23.

[22] Shell Sustainability Report, p. 52. Available online at http://reports.shell.com/sustainability-report/2015/servicepages/downloads/files/entire_shell_sr15.pdf

## 4. Results and discussion: values retrieved for other companies

The choice of the producers included in this analysis was made using the list of the largest oil and gas companies by revenue, in USD in 2015[23]. From this list, we selected the companies above the 1% of the market share, as shown in the following table:

| # | Company | Billions $ | Market share % | |
|---|---|---|---|---|
| 1. | Saudi Aramco | 478.00 | 8.31 | 34.77 |
| 2. | Sinopec | 455.50 | 7.92 | |
| 3. | China National Petroleum Corporation | 428.62 | 7.45 | |
| 4. | PetroChina | 367.98 | 6.40 | |
| 5. | Exxon Mobil | 268.90 | 4.68 | |
| 6. | Royal Dutch Shell | 265.00 | 4.61 | |
| 7. | Kuwait Petroleum Corporation | 251.94 | 4.38 | |
| 8. | BP | 222.80 | 3.88 | |
| 9. | Total SA | 212.00 | 3.69 | |
| 10. | Lukoil | 144.17 | 2.51 | |
| 11. | Eni | 131.82 | 2.29 | |
| 12. | Valero Energy | 130.84 | 2.28 | |
| 13. | Petrobras | 130.00 | 2.26 | |
| 14. | Chevron Corporation | 129.90 | 2.26 | |
| 15. | PDVSA | 128.44 | 2.23 | |
| 16. | Pemex | 117.50 | 2.04 | |
| 17. | National Iranian Oil | 110.00 | 1.91 | |
| 18. | Gazprom | 106.30 | 1.85 | |
| 19. | Petronas | 100.74 | 1.75 | |
| 20. | China National Offshore Oil | 98.53 | 1.71 | |
| 21. | Marathon Petroleum | 97.81 | 1.70 | |
| 22. | PTT | 93.55 | 1.63 | |
| 23. | Rosneft | 91.72 | 1.60 | |
| 24. | JX Holdings | 90.67 | 1.58 | |
| 25. | Engie | 89.64 | 1.56 | |
| 26. | Statoil | 82.48 | 1.43 | |
| 27. | Indian Oil Corporation | 81.55 | 1.42 | |
| 28. | Sonatrach | 76.10 | 1.32 | |
| 29. | Reliance Industries | 73.10 | 1.27 | |
| 30. | Pertamina | 70.65 | 1.23 | < 1% |
| | Others | 623.27 | 10.84 | |
| | Total amount >>>> | 5.749.52 | 100.00 | |

**Table 1:** *Oil companies revenues and cut off for values of market share less than 1%.*

[23] From the website "World Atlas": http://www.worldatlas.com/articles/biggest-oil-companies-in-the-world.html

This choice amounts to select the first 30 companies by revenue (2015). These, in turn, share the 89% of the entire oil market. For all of these companies we have found the production of oil and the SRs, where in some cases the data of both direct and indirect emissions are reported. The values found for these companies are listed in the following table and compared with production and revenues in the same year (unless otherwise specified).

| Oil Company name [N or P \| O or B][24] | Revenues [$10^9$ $] | Production (oil & gas) [b/y] | EROI [D \| I][25] |
|---|---|---|---|
| 01. Saudi Aramco [N \| O] | 478.00 | 4,079,118,750.00 | 51.85 |
| 02. Sinopec [N \| O] | 455.50 | 471,910,000.00 | 1.67 |
| 03. China National Petroleum [N \| O] | 428.62 | 1,369,142,168.99 | NA |
| 04. PetroChina [N \| O] | 367.98 | 1,493,900,000.00 | 3.63 |
| 05. Exxon Mobil [P \| O] | 268.90 | 2,147,860,750.00 | 7.59 |
| 06. Shell [P \| O] | 265.00 | 1,095,000,000.00 | 7.75 \| 6.88 |
| 07. Kuwait Petroleum [N \| O] | 251.94 | 1,058,500,000.00 | 19.86 |
| 08. BP [P \| O] | 222.80 | 1,196,105,000.00 | 11.23 \| 9.74 |
| 09. Total SA [P \| O] | 212.00 | 856,655,000.00 | 10.81 |
| 10. Lukoil [P \| O] | 144.17 | 890,000,000.00 | 5.83 |
| 11. Eni [P \| O] | 131.82 | 932,856,050.00 | 10.43 |
| 12. Valero [P \| B] | 130.84 | NA | NA |
| 13. Petrobras [N \| B] | 130.00[26] | 1,018,350,000.00 | 5.65 |
| 14. Chevron [P \| O] | 129.90 | 1,283,971,450.00 | 9.70 |
| 15. PDVSA (Venezuela) [N \| O] | 128.44 | 1,373,611,800.00 | NA |
| 16. Pemex [N \| O] | 117.50 | 1,017,620,000.00 | 7.88 |
| 17. National Iranian Oil [N \| O] | 110.00[27] | 1,624,250,000.00 | 1.30 |
| 18. Gazprom [N \| O] | 106.30 | 2,905,775,054.29 | 11.65 |
| 19. Petronas [P \| O] | 100.74 | 894,862,500.00 | 7.93 |
| 20. CNOOC [N \| O] | 98.53 | 719,973,411.17 | 11.20 |
| 21. Marathon Petr. [P \| B] | 97.81 | 465,353,100.00 | 11.38 \| 8.41 |
| 22. PTT (Thailand) [N \| O] | 93.55 | 241,060,000.00 | 24.95 \| 24.89 |
| 23. Rosneft [N \| O] | 91.72 | 2,258,218,368.75 | 21.14 \| 13.12 |
| 24. JX Holdings [P \| B] | 90.67 | 49,006,000.00 | 2.68 |
| 25. Engie [P \| B] | 89.64 | 209,779,126.80 | NA |
| 26. Statoil [N \| O] | 82.48 | 1,073,000,000.00 | 28.37 |
| 27. Indian Oil Corporation [N \| B] | 81.55 | 422,016,571.42 | 3.70 |
| 28. Sonatrach [N \| O] | 76.10[28] | 370,059,300.00 | 22.56 |

[24] N = national company | P = private company; O = core business: oil & gas extraction | B = core business: refinery or/and other business.

[25] D stands for "direct emissions" and I for "indirect".

[26] Revenue in 2013.

[27] Revenue in 2012.

[28] Revenue in 2012.

| | | | |
|---|---|---|---|
| 29. Reliance Industries [P \| B] | 73.10 | 17,220,213.80 | 28.58 |
| 30. Pertamina [N \| O] | 70.65 | 219,636,100.00 | 8.04 |
| TOTAL | 5,126.25 | 31,754,810,715.23 | 16.79[29] |

**Table 2:** *Oil companies: revenues 2015, production and EROI*

In Appendix 2, we discuss in detail the present situation for some companies and the method we used to retrieve the missing data. In the case of Saudi Aramco, the biggest oil company in the world, the methodology adopted is totally different. In Saudi Aramco Annual Report[30] there are no emissions data, but there is (p. 66) the energy intensity required to produce one barrel of oil equivalent: 108,000 BTU (in 2015). It is possible to compare this value directly with the BTU content of a barrel of crude oil (5,600,000). The $EROI_{INC}$, in this case, is obtained by dividing this latter quantity by the content of BTU in an oil barrel (108,000)[31], i.e.:

$$EROI_{SA} = \frac{5{,}600{,}000}{108{,}000} = 51.85$$

This value is very high, but it must be considered an EROI "at the wellhead". Unfortunately, it is the only one that we can calculate by the available data and therefore cannot be compared with the EROI values obtained for the other petroleum companies. A way to estimate the Saudi Aramco's EROI "at the gate" is using the following figure[32]:

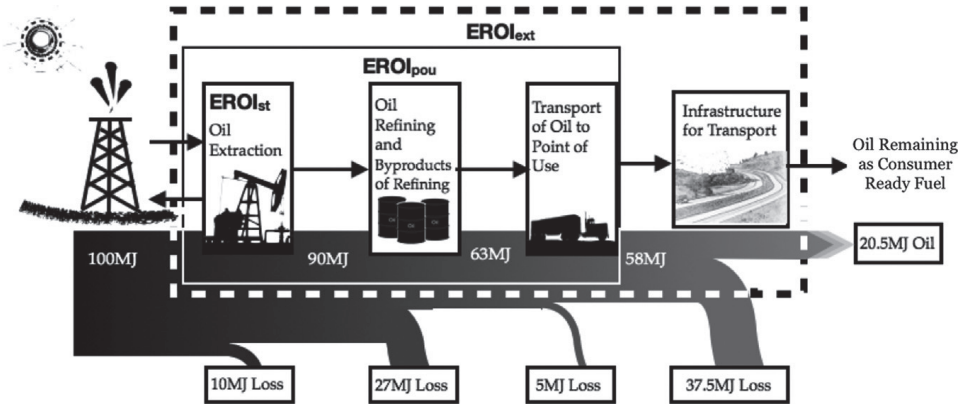



**Figure 3:** *Boundaries of various types of EROI analyses and energy loss associated with the processing of oil as it is transformed from "oil at the well-head" to consumer ready fuels.*

[29] Weighted mean for all companies calculated only for direct emissions.

[30] One complication to retrieve data concern the "place": sometimes there are in the Sustainability Report, some other times are in the Annual Report, other are on the website of the company.

[31] In appendix 2 the first case discussed is Saudi Aramco and there we have described the entire procedure to obtain exactly this value.

[32] In Hall C. A. S., Lambert J. G., Balogh S. B. (2014), with the permission to reproduce it. The graph is based on calculations in Hall C. A. S., Balogh S., Murphy D. (2009).

The expression "at well-head" exactly means, in correspondence of the picture, 90 MJ (10 MJ are used to extract). The losses, always in the picture, until $EROI_{ext}$, and are 58 MJ and thus we need an appropriate proportionality factor to estimate the Saudi Aramco's EROI "at the gate". Such a factor is determined by the relationship:

$$\frac{51.85}{x} = \frac{90}{58}$$

Therefore the Saudi Aramco's EROI at the gate can be estimated as:

$$EROI_{SAgate} = \frac{51.85 \times 58}{90} = 33.4.$$

The EROI values are, as shown, fairly close one to each other and, using the information of figure 3, the Saudi Aramco value is closer than before. An interesting point of view could be the introduction of an element of proportionality between revenues, production and EROI, which may help to distinguish among different corporations. In any case, we will see in section 5 ("Remarks about Corporate EROI") in which way the calculated values change[33]. In figure 4, we report the data where each dot has a size proportional to the ratio between revenue and EROI[34]:

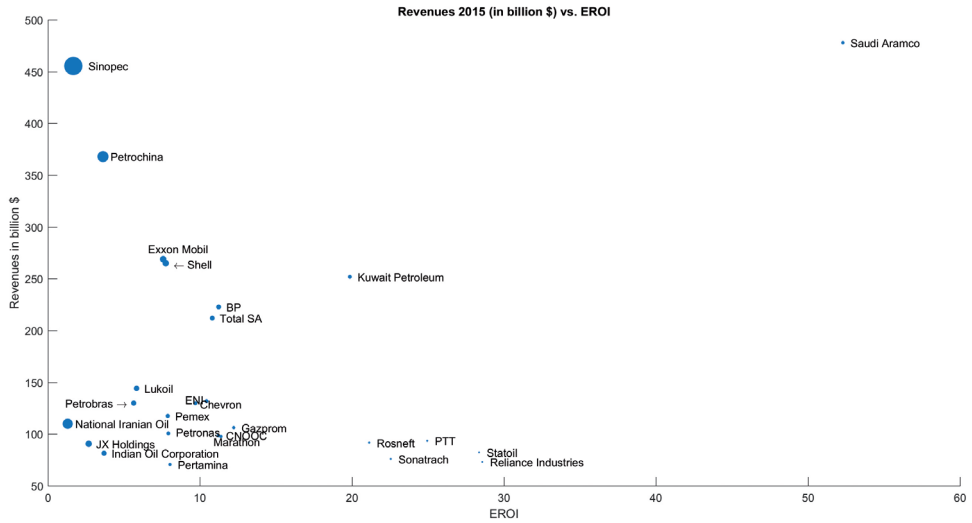



**Figure 4:** *Revenues 2015 (in billion $) vs. EROI. The size of the dot is proportional to the ratio between Revenue and EROI.*

[33] For example, even if only one value has been changed, the weighted mean value for all companies change of various points and – if we use the EROI just calculated for Saudi Aramco: 33.4 – it becomes 14.12 instead 16.79. This happens because Saudi Aramco is the biggest oil company.

[34] In this figure with Saudi Aramco's EROI equal to 51.85.

Even if the graph does not exhibit a clear correlation, however, the expected result is a tendency line that goes up when the revenue of the companies is increasing. The cause is that, probably, the biggest companies have higher revenues and, as expected, higher values of EROI. This raises the question of the outliers. In particular, we expect differences between private vs. national(ized) companies. Indeed, in the set of oil companies there are substantial differences between some national companies (government-controlled) and private ones. Often the latter have some stronger constraints with respect to the former, especially about transparency of financial statements, mandatory declarations and so on. Private companies, for example, have rules that are more rigorous because they are listed on the stock market, but this has more to do with the reserves (which are assets that contribute to determine the value of the stocks) rather than with production (that is well known). There are other factors concerning national companies: their budgets may be less transparent because informations about their activities are considered strategic by the controlling governments. Precise information on production, stocks, estimated reserves, refining capability, turnover, etc., would be an indicator of the vulnerability of these countries to the fluctuations in the oil market. This happens (1) because oil production is required to maintain high rates of economic growth (such as the People's Republic of China) and (2) because the economies and commercial balances of oil producing countries (such as Saudi Arabia) are heavily dependent on exports of petroleum products. In some important cases – the biggest oil companies are Arabian, Chinese and Russian – we were not able to retrieve the data of production from SRs and have found them in academic papers[35]. Picture 5 shows the difference in $R^2$ for national vs. private companies.

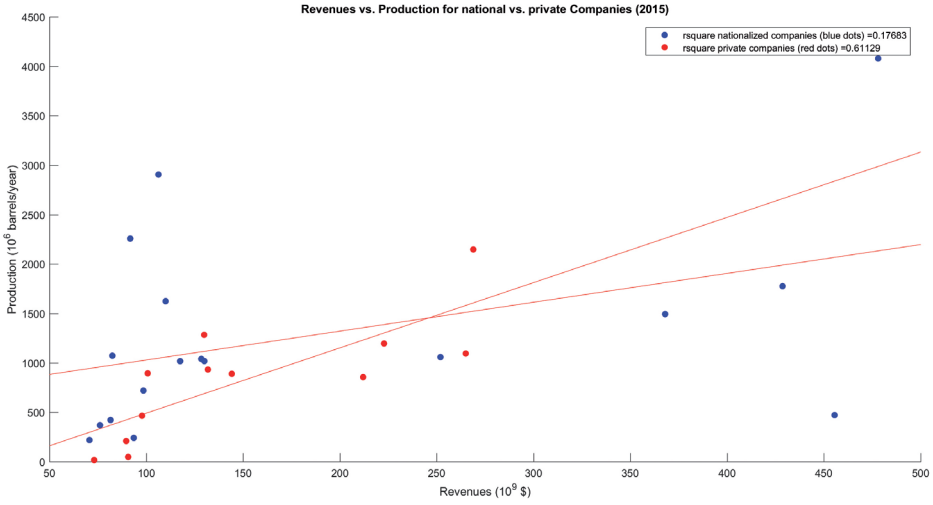



**Figure 5:** *Revenues 2015 (in billion $) vs. production, with line tendency and value of $R^2$ for national vs. private companies.*

[35] Safronov A., Sokolov A. (2014); Zhao-Yang K., Xiu-Chang D., Qian S., Xin W., Da-Lin T., Gui-Xian L. (2016).

Another interesting comparison can be done between companies that have their main core business in oil production and companies that have not. The fit is reasonably good and, not surprisingly, better for the second ones than for the first ones, as shown in picture 6:

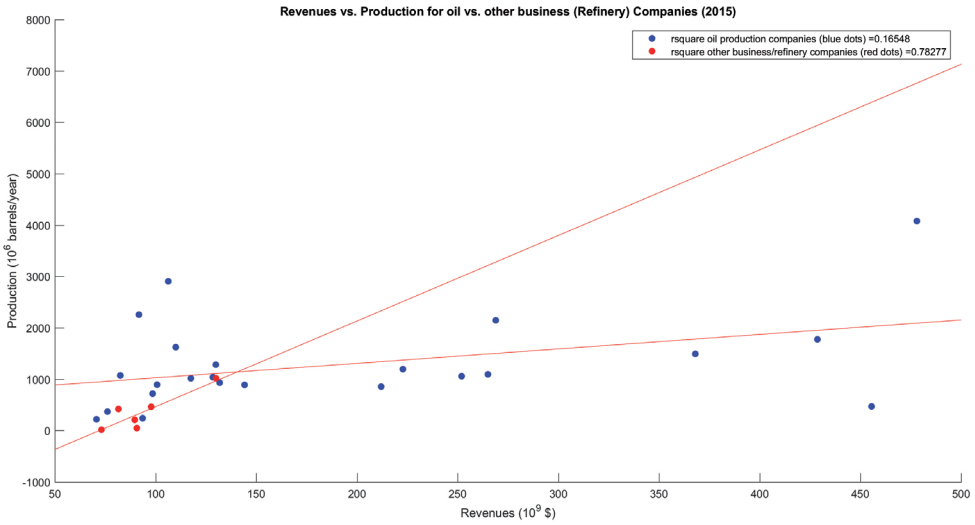



**Figure 6:** *Revenues 2015 vs. production, with line tendency and $R^2$ subdivided by core business (oil vs. other/refinery).*

The better fit for companies that not have a core business in oil production is explainable by more homogeneous operative conditions. Indeed, oil production means working in more variable conditions and take risks: prospecting in soil and offshore, failing prospecting, variable quality of oil and so on. The companies that refine oil probably can manage better their costs; they receive oil with well-known features and consequently can estimate with great accuracy costs, prices, and gains.

Figure 5 emphasizes the difference between public and private companies. The private companies show a closer linear relationship between production and revenues while, for the public ones the correlation is weaker: this is the meaning of the graph. Figure 6 similarly puts revenues and production in relation to companies that deal mainly with refining vs. companies that deal with mining. As expected, the risk margin of a company that conducts prospecting and, in general, mining is higher; on the contrary, it appears much lesser for those involved in refining, due to a certain control on the quality of the raw material.

It should be commented on the choice of revenues instead of other economic parameters as EBIT (Earnings Before Interest and Taxes) or EBITDA (Earnings Before Interest and Taxes, Depreciation and Amortization).

The aim of relating revenues with production (and not only EROI) was simply that of highlighting any relationship among oil companies that make mainly extraction compared with those that deal with refining and, in the other graph, among public companies vs. private. The graphs show a more significant linear correlation between revenues and production in the case of companies having refinery as their core business, in comparison with those dealing with oil/gas extraction. Similarly, a better correlation is found for purely private companies than for public companies. In our opinion considering EBIT would introduce an additional variable into the calculation, which is unnecessary for the purposes of this article, with the risk to complicate uselessly the search for a possible correlation with production: EBIT shows indeed a relatively great variability along the years and could even take negative values. Furthermore, there is no unequivocal definition of EBIT and this parameter is rather different from EBITDA (https://www.business-case-analysis.com/earnings-before-interest-and-taxes.html).

As a result, companies follow different definitions and it becomes difficult to know which is actually used in their budgets. Finally, the available data seems to be rather incomplete (they do not cover all companies considered in this work). Both these indices are certainly interesting for possible correlations and could be useful for further investigation, in principle, but only after an accurate and nontrivial checking of the company financial statements.

## 5. Remarks about corporate EROI

### *5.1 Limits of the method*

An important drawback of the method is the assumption that oil is a globally homogeneous commodity, and therefore it has the same composition and properties all over the different oil regions and fields. This is not the case: a simple graph reporting the API degree vs sulphur content of oils can show it[36]. In spite of that, many analyses take average values of energy content and density of oil as if this quite severe assumption is correct. As an illustration, it is apparent that the complete combustion of a mole of a pure hydrocarbon containing x carbon and y hydrogen atoms (molecular formula $C_xH_y$) will produce x moles of $CO_2$. The corresponding weight ratio of produced $CO_2$ to burned $C_xH_y$ is thereby given by the formula:

$$R = \frac{x \times MW_{CO2}}{MW_{C_xH_y}} = \frac{x \times MW_{CO2}}{x \times MW_C + y \times MW_H} = \frac{MW_{CO2}}{MW_C + \frac{y}{x} \times MW_H} \qquad \text{[eq. 1.5]}$$

where $MW_{CO2}$, $MW_{CxHy}$, $MW_C$ = 12.0107 and $MW_H$ = 1.00794 denote the molecular/atomic weight of $CO_2$, $C_xH_y$, C and H, respectively. The relationship shows

[36] ENI (2015).

that the smaller the number y of H atoms compared to the number x of C atoms, the larger the emission/combustible weight ratio. The value R=3.14 is obtained when y/x=2. For paraffins, whose y/x ratio is (2x+2)/x>2, our reference value 3.14 overestimates the actual ratio R, but the relative difference RD=(R-3.14)/3.14 is very small and rapidly decreases below 1% when the number of carbons grows (see Table 3-a).

In contrast, 3.14 provides an underestimate to the true value of R in the case of alicyclic and aromatic hydrocarbons, where the y/x ratio turns out to be significantly smaller than 2, as illustrated in Table 3-b.

| Compound | Molecular formula | Molecular weight | Emission/combustible weight ratio R | Relative difference RD (%) |
|---|---|---|---|---|
| Pentane | $C_5H_{12}$ | 72.1488 | 3.0499 | -2.79 |
| Decane | $C_{10}H_{22}$ | 142.2817 | 3.0931 | -1.42 |
| Pentadecane | $C_{15}H_{32}$ | 212.4146 | 3.1078 | -0.95 |
| Icosane | $C_{20}H_{42}$ | 282.5475 | 3.1152 | -0.71 |
| Pentacosane | $C_{25}H_{52}$ | 352.6804 | 3.1196 | -0.57 |
| Triacontane | $C_{30}H_{62}$ | 422.8133 | 3.1226 | -0.48 |
| Pentatriacontane | $C_{35}H_{72}$ | 492.9462 | 3.1247 | -0.41 |
| Tetracontane | $C_{40}H_{82}$ | 563.0791 | 3.1263 | -0.36 |
| Pentatetracontane | $C_{45}H_{92}$ | 633.2120 | 3.1276 | -0.32 |
| Pentacontane | $C_{50}H_{102}$ | 703.3449 | 3.1286 | -0.29 |
| Pentapentacontane | $C_{55}H_{112}$ | 773.4778 | 3.1294 | -0.26 |

**Table 3-a:** *Values of the ratio R for paraffins of increasing molecular weight. When the number of carbons is sufficiently large R appears very close, although always smaller than, to the reference value of 3.14.*

| Compound | Molecular formula | Molecular weight | Emission/combustible weight ratio R | Relative difference RD (%) |
|---|---|---|---|---|
| Benzene | $C_6H_6$ | 78.1118 | 3.3805 | 7.74 |
| Naphthalene | $C_{10}H_8$ | 128.1705 | 3.4337 | 9.44 |
| Anthracene | $C_{14}H_{10}$ | 178.2292 | 3.4569 | 10.18 |
| Pyrene | $C_{16}H_{10}$ | 202.2506 | 3.4816 | 10.96 |
| Benzo(a)pyrene | $C_{20}H_{12}$ | 252.3093 | 3.4885 | 11.18 |

**Table 3-b:** *Calculated values of R for some alicyclic and aromatic hydrocarbons of increasing molecular weight. The estimates always exceed the reference value of 3.14. Significant deviations from the reference value occur particularly when the H/C number ratio is small.*

Consequently, a different composition of the oil produced and processed by a company may result in a ratio between the amount of $CO_2$ actually corresponding to the company production and the production itself possibly different from the value 3.14 we have taken as a reference. Since the elemental composition of oils typically varies within rather narrow ranges[37]. However, one may assume that the opposite effects of paraffins, with an H/C number ratio larger than 2, and alicyclic and aromatic hydrocarbons, whose H/C number ratio is significantly smaller, counterbalance each other and that the different composition of the various kinds of oil does not affect severely the result. Another possible limit of the method is the assumption that the companies cover the entire production delivery chain. In fact, the prevalence of upstream over downstream activities or vice versa would affect the EROI, in the first case making it closer to the value "at the well head". This limit cannot be overcome without a painstaking analysis of the production chain of each company, which is beyond the scope of this investigation.

Probably the most important drawback of the proposed method is exactly the fact that it uses a non-energy metric, and thus the EROI evaluation is in principle different. We are aware of this problem and we acknowledge it numerically in the final part of this section. Correcting for this approximation seems, however, to be a nontrivial task for the reasons we discuss below:

a) first of all it should be clear that the proxy we are proposing is intrinsically approximated. We do not claim to have found a precise alternative to the detailed evaluation of energy metrics, but only propose an approximate, easily computable proxy, for which simple corrections may be applied;

b) one possible criticism is that renewable energy (producing a negligible amount of $CO_2$) is in fact used even in fossil fuels industry. We are estimating corporate EROI and generally the corporation we are analyzing are very big and their activities are diffused in the world; in the mean the importance of renewable energy in their operations is expected to be essentially similar to the typical relevance of renewables in electrical energy conversion, i.e. relatively low. In very particular countries as Norway the electric energy is almost all renewable. In a web page dedicated to the basic facts about Norway energy policy[38] we can read that: "The electricity generation sector is virtually emission-free. However, energy use in transport, manufacturing, oil and gas production and for heating still results in greenhouse gas emissions". Due to the geographic location of the upstream, we believe that the importance of renewables is extremely

[37] Speight J. G. (2001).

[38] https://energifaktanorge.no/en/om-energisektoren/verdt-a-vite-om-norsk-energipolitikk/

limited; in a 2015 review[39] the use of solar energy in oil and gas industry is considered promising. In the same review, it is conjectured that it may cover 5% of the total energy requirements in 2035 and it is also claimed that: "Most of the energy (nearly 90%) is derived directly from the produced oil and gas. Electricity, which amounts to 10% of the consumed energy, is supplied normally from the electric power grid and does not include the electricity generated on site at some locations". Therefore, even in the case of Norway the maximum difference may only attain 10%. In another recent review[40] some case studies are presented. One of them concerns the Utsira field in Norway, but no general evaluation is done on the role of renewable energy in oil and gas industry in the world. This confirms that the error due to application of renewable energy in oil and gas industry is growing but, at the same time, that at present it is generally small and cannot significantly change our results. We may estimate that the percentage of renewable energy currently used in the oil and gas industry is of the order of few percent;

c) the ratio of energy per unit mass of $CO_2$ produced by different fossil fuels is obviously different. May we acknowledge for it? Energy produced per unit mass of emitted $CO_2$ is higher for gas fuel by 1/3 than for oil; in principle, we could convert the $CO_2$ metric into an energy metric knowing the ratio of gas/oil in the two terms of the EROI and introducing an opportune correction factor.

It is easy to evaluate this correction in the production term (the numerator) for the relative importance of the gas (it has been already tabulated in our data for each corporation); the same detailed estimate is however impossible for the consumption term (the denominator), as the needed data are not present in the Sustainability Reports.

We may correct the denominator term only by referring to a mean composition estimate of the energy used, which is however different for each step of the industrial cycle. To do this we may use the estimate of the cited review[41], which corresponds to about 48% of the total energy employed in the oil and gas sector (another 43% is from oil and the remaining 9% electric energy). Finally, both these corrections may be applied to the data. As for the correction of electric energy in the denominator and given the reduced role of renewables in fossil fuel industry, we propose simply to divide the 9% in proportion between oil and gas, 53% for gas and 47% for oil. A couple of simple algebraic equations allows to perform the correction for the denominator, considering that for 1MJ one produces 1.6 mol of $CO_2$ from oil and only 1.2 from gas:

$$CO_{2(oil)} + CO_{2(gas)} = CO_{2(total)}$$

[39] Absi Halabi M., Al-Qattan A., Al-Otaibi A. (2015).
[40] Choi Y., Lee C., Song J. (2017).
[41] Absi Halabi M., Al-Qattan A., Al-Otaibi A. (2015).

$$\frac{1.2\ CO_{2(oil)}}{1.6\ CO_{2(gas)}} = \frac{0.47}{0.53}$$

The solution of the equation system gives the two unknowns in terms of $CO_{2(total)}$:

$CO_{2(oil)} = 0.5418\ CO_{2(total)}$ and

$CO_{2(gas)} = 0.4582\ CO_{2(total)}$

Now the denominator of EROI may be rewritten in terms of energy using as a numerical correction factor 1.1527 for all the corporate EROI values. The $CO_2$-metric EROI and the energy-metric EROI recalculated with the previous correction are shown in Table 4.

| Company | $CO_2$EROI | $CO_2$EROI corrected |
|---|---|---|
| Saudi Aramco | 52.29 | 46.53 |
| Sinopec | 1.67 | 1.55 |
| Petrochina | 3.62 | 3.52 |
| Exxon | 7.58 | 7.25 |
| Shell | 7.75 | 7.07 |
| Kuwait | 19.86 | 17.71 |
| BP | 11.23 | 10.97 |
| Total | 10.81 | 10.37 |
| Lukoil | 5.83 | 5.35 |
| Eni | 10.43 | 9.99 |
| Petrobras | 5.64 | 5.23 |
| Chevron | 9.70 | 9.13 |
| Pemex | 7.88 | 7.39 |
| National Iranian Oil co. | 1.30 | 1.39 |
| Gazprom | 12.22 | 13.16 |
| Petronas | 7.92 | 7.53 |
| Cnooc | 11.20 | 10.39 |
| Marathon | 11.38 | 10.22 |
| PTT | 24.95 | 24.79 |
| Rosneft | 21.13 | 19.35 |
| Jx Holdings | 2.68 | 2.44 |
| Statoil | 28.36 | 26.79 |

| | | |
|---|---|---|
| Indian Oil Corporation | 3.69 | 3.25 |
| Sonatrach | 22.55 | 22.12 |
| Reliance Industries | 28.57 | 32.50 |
| Pertamina | 8.03 | 8.22 |
| TOTAL >>> | 16.79 | 15.03 |

**Table 4:** *Corporate EROI values calculated without and with the correction needed to take into account the different CO2 emission rate per unit energy of oil and gas.*

As one can see, the corrections are very small and do not change the general trend of the results.

### *5.2 Other considerations*

It is rather simple to find out the numerator of the $EROI_{INC}$ ratio, but some difficulties could arise for the number to use at the denominator. The example of the Shell SR can clarify this kind of problem. Shell reports to comply with the indications provided in the *Greenhouse Gas Protocol*, to calculate the emissions. The data reported for 2015 are 72 million tons of $CO_2$ equivalent (direct emissions), subdivided in:

- 68 million tons of $CO_2$;
- 119 thousand tons of $CH_4$;
- 1 thousand tons of $N_2O$;
- 18 tons of HFCs.

There are also 9 million tons of $CO_2$ equivalent, declared as indirect emissions and, in the same table[42], we can find 88 thousand tons of $SO_2$, 104 thousand tons of $NO_2$ and 125 thousand tons of Volatile Organic Compounds (VOCs).

When the reports are so detailed, the problem could be: which data are useful for our calculations? Fortunately: (1) other emissions, except $CO_2$, are often a little percentage relative to the total amount, and (2) many reports offer directly the values in $CO_2$ equivalent. In this case, the approximation consists in neglecting the contribution of $SO_2$, $NO_2$ and VOCs, because they represent only the 0.38% of total emissions.

The Company declares that the 45% of direct emissions come from refinery activities and chemical plants in downstream side of production, while the 50% of emissions is referred to the upstream activities of oil and gas production. GHG indirect emis-

[42] Page 52 of Shell Sustainability Report 2015.

sions are related to the energy consumption bought for electricity and heating by third parties and are calculated following the World Resources Institute guidelines.

In Table 5, we report some EROI values for the Shell Company, found using different data sources.

| Case | numerator [million tons $CO_2$] | denominator [million tons $CO_2$] | EROI |
|---|---|---|---|
| a. | 471.35* | 72[α] | 6.55 |
| b. | 471.35* | 72+9[β] | 5.82 |
| c. | 471.35* | 68.12** | 6.92 |
| d. | 471.35* | 81.32*** | 5.80 |
| e. | 560**** | 72 | 7.78 |
| f. | 560 | 72+9 | 6.91 |
| g. | 560 | 68.12 | 8.22 |
| h. | 560 | 81.32 | 6.89 |

[α] Direct emissions.
[β] Direct + indirect emissions.
* This is the value obtained by converting 3 million barrels extracted into $CO_2$ equivalent.
** This is a quantitative evaluation about the emissions and not a measure of the impact in terms of GHG. So in this case it could be useful to add each contribution, obtaining a value lesser than 72 – calculated, instead, multiplying gas emissions by the corresponding Global Warming Potential (GWP), following the GHG Protocol, where GHGs are calculated as Emission Data × GWP.
*** To the values of direct and indirect emissions, we can add the contribution of $SO_2$, $NO_2$ and VOCs. We can observe a very small variation with respect to the b. case.
**** Shell Company provides an estimate to the emissions of his products. Quoting the report: «We estimate that the $CO_2$ emissions from the use of our refinery and natural gas products were around 560 million tons in 2015», p. 36.

**Table 5:** *EROI values for the Shell Company, obtained using different data sources.*

The final values estimated for the corporate EROI are of the same order of magnitude of those found by Hall, Powers and Schoenberg (2008) and Gagnon N., Hall C. A. S., Brinker L. (2009). If allowance is made for the approximations introduced and considering some corporate omissions, the estimates do not exceed the value of 10.

## 6. Some comparisons with other EROI estimates

Some interesting data can be found in the literature about companies that had no clear policy about SR and rules about emissions. Looking at Chinese and Russian companies, in particular, we have obtained some rather similar EROI values. While for Sinopec our calculation was based only on a statement (for details see Appendix 2)

and therefore the values are different[43], for CNOOC our calculation gives an EROI equal to 11.20 (for 2015, and 10.39 with the correction factor) and, for Zhao-Yang K., Xiu-Chang D., Qian S., Xin W., Da-Lin T., Gui-Xian L. (2016) 9.9 with 2009 data. Even if, in meanwhile, «In terms of refining, in 2009, CNOOC's 12 Mt/a Huizhou Refinery Project Phase I was completed and put into production, marking the CNOOC entrance into the refining business (CNOOC Annual Reports)»[44], so that it is plausible a small increment of EROI from 2009 to 2015.

For some Russians companies (Gazprom, Rosneft) rather similar values have been determined. Gazprom has EROI = 12.22 (and 13.16 corrected) according to our calculation, while Safronov A., Sokolov A. (2014) estimates this value equal to 13.3 for 2012. The Rosneft EROI estimate in Safronov A., Sokolov A. (2014) is 22.2 (without embodied energy, 2012), whereas our approach provides a value of 21.13 (without indirect emissions, 2015) and 19.35 with the correction factor.

Finally, the last positive comparison comes from Court V., Fizaine F. (2017). We have tried to estimate the global EROI worldwide using the production of the companies (whenever we were able to calculate the EROI). What we have found in SRs, subdividing oil and gas - where the data are not aggregate - is a prevalence of oil production (67% the total amount for analyzed companies) than gas (33%). We have simply calculated a weighted mean of all values and the global EROI found is 16.79 (15.03 with the correction factor). Obviously, there is a kind of "compensation" between two major companies (Saudi Aramco and Sinopec): the first one has an EROI too high (52.29 calculated "at well-head") and the second one a value too low (1.67, based only on a conjecture extracted by a statement). The global EROI for hydrocarbons calculated in this way was compared with Court V., Fizaine F. (2017)[45], both in a graphic way and by using the numerical data[46], and its value (for 2012) is 17.67. These estimates do not seem too far from each other, with all the approximation and the caution we can use. From Table 4 of Section 5.1 one can see that also the correction of the original $CO_2$ metric and its transformation in a closer energy metric do not change in a significant way the situation.

### *6.1 The Shell time series*

By this method, I have also tried to calculate a time series with the available data for the Shell company. I have chosen Shell because it is the company that has shown high

[43] For Zhao-Yang K., Xiu-Chang D., Qian S., Xin W., Da-Lin T., Gui-Xian L. (2016) standard EROI for 2013 is 10.6 and for the present analysis 1.67.

[44] Zhao-Yang K., Xiu-Chang D., Qian S., Xin W., Da-Lin T., Gui-Xian L. (2016), p. 798.

[45] Page 152, picture 9 top right.

[46] Victor Court, personal communication.

sensibility to the sustainability and it is quite easy to find all Sustainability and Annual Reports. The results are illustrated in the following graph.

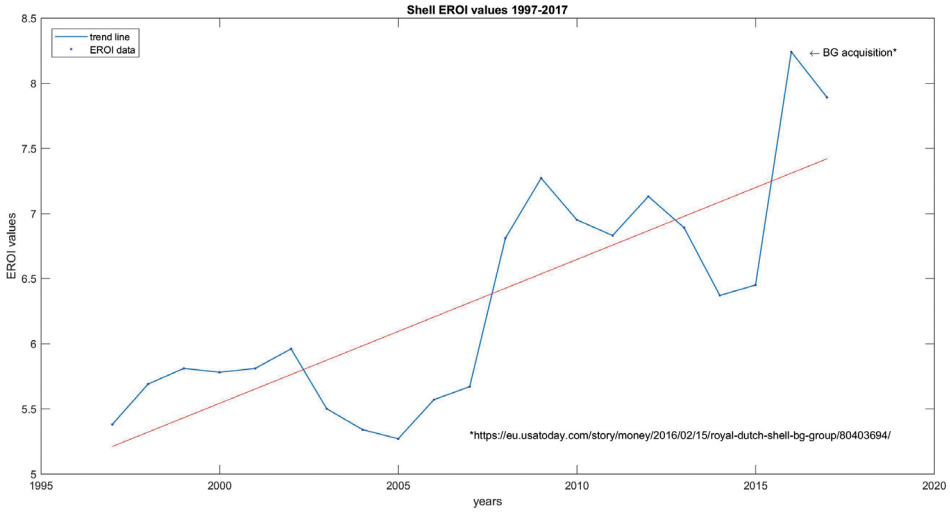



**Figure 7:** *The Shell EROI time series with a trend line.*

As we can see, there are no great changes year by year and the only "peak" in some way significant is in correspondence of 2016, when the company bought the BG group[47], even if the growing up trend is due also probably to a better internal organization and efficiency.

[47] https://eu.usatoday.com/story/money/2016/02/15/royal-dutch-shell-bg-group/80403694/

# Chapter 2.
# Describing and modeling the oil market

## 1. Introduction

The Anthropocene, the era in which humans have the most powerful influence on global ecology, is started since the mid-twentieth century[1]. The accelerating pace of energy use, greenhouse gas emissions, and population growth have thrust the planet into a massive uncontrolled experiment. The graphs in figure 1 and 2 show (1) the direct correlation between energy availability and population growth and (2) the energy per capita along the last two centuries. In this situation, the role of energy systems is predominant: that is why my research started to investigate the relationship between the phase-plot of worldwide oil production (1965-2016) and its price.

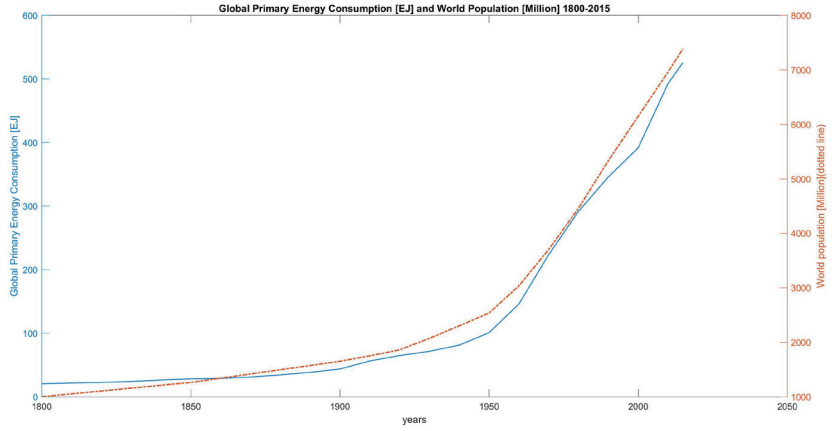



**Figure 1:** *Global energy consumption (in exajoule) and World population 1800-2015. The data on World population come from UN (1999), page 5, and the UN website. About Global Primary Energy Consumption, the data come from Smil (2017), Appendix A, pp. 240-241.*

[1] Not all researchers agree about the start of this period, but, following McNeill, Engelke (2016), we consider the beginning after WWII.

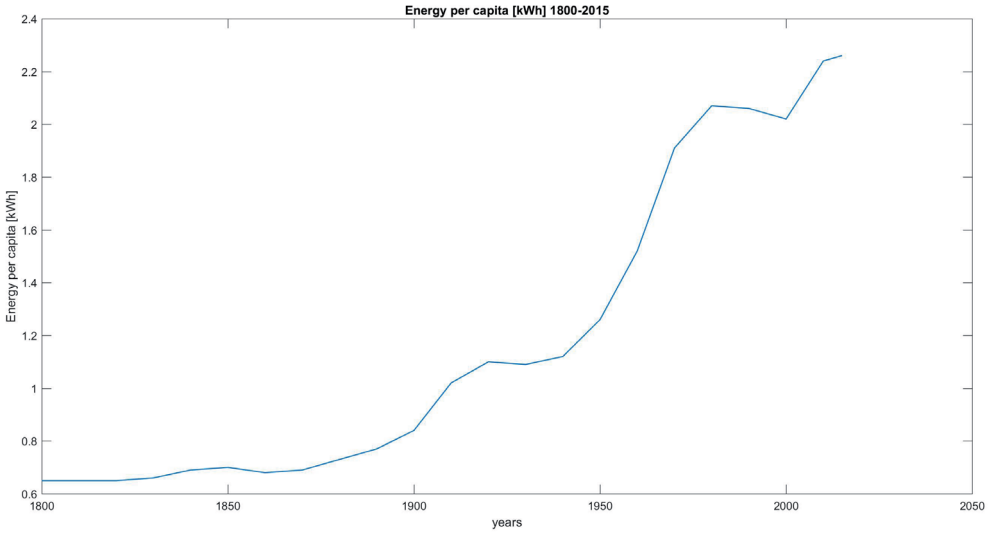



**Figure 2:** *Energy per capita worldwide. This graph was obtained dividing the values of energy consumption in Smil (2017) by the values of the World population.*

The behavior of complex systems is one of the most intriguing phenomena investigated by recent science; natural and artificial systems offer a wide opportunity for this kind of analysis. The energy conversion is both a process based on important physical laws and one of the most important economic sectors; the interaction between these two aspects of the energy production suggests the possibility to apply some of the approaches of the dynamical systems analysis. In particular, a phase plot, which is one of the methods to detect a correlation between quantities in a complex system, provides a good way to establish qualitative analogies between the ecological systems and the economic ones, and may shed light on the processes governing the time evolution of the system.

The aim of this chapter is to highlight the analogies between some peculiar characteristics of the oil production vs price and some behavioral mechanisms found in Nature, and show in which way such characteristics are similar to each other.

## 2. A brief history

In a previous study[2], we tried to show how a phase plot of oil production vs. the price has an irregular trend (random behavior) with two important features that identify the oil market as basically inelastic (The lines in red in figure 3). The graph, even

[2] Celi L., Della Volpe C., Pardi L., Siboni S. (2017).

if only qualitatively, shows two peaks upward where the oil price became very high in few years, and then rapidly decreases[3].

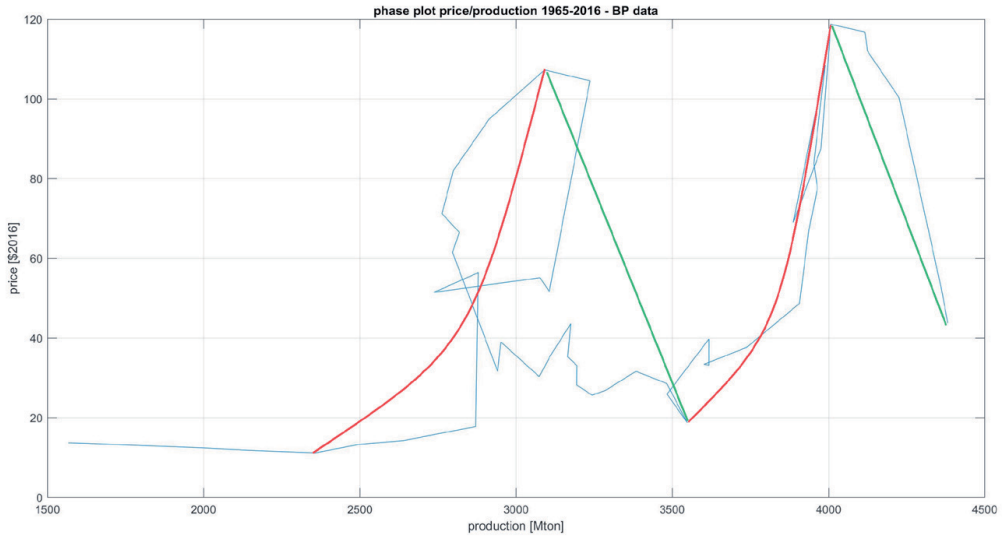



**Figure 3:** *The phase-plot for oil production and price from 1965 to 2016. In the "erratic walk" of this plot, four movements of price-production were highlighted: two ascending (red lines) and two descending (green lines).*

This kind of "swinging behavior" recalls some typical phenomena, investigated by some theories in the domain of complex systems. In particular, this is the case of Thom's catastrophe theory[4].

## 3. Method

The behavior illustrated in the phase plot (figure 3) in his simpler version could be represented as follows. We can imagine having two oil wells: one at a lower cost of extraction (e.g., 100 $/barrel) and one higher (200 $/barrel)[5], as schematically described in figure 4. If in our hypothetical world the consumption is in the range between 0 and 1,000 barrels/day, we use the oil at a lower price (green rectangle), with a price (ideally) inside the range 0-100 $/barrel. If the intensity of consumption grows, we need to use the second stock of oil at the higher price (red rectangle). In this case, the oil price increases rather rapidly, and the corresponding phase plot is illustrated in figure 5.

[3] Obviously, we are looking at the general trend, without considering the "erratic walk" behavior in the middle.

[4] Thom R. (1972), cited in Scheffer M. (2009).

[5] These values are obviously arbitrary and are used only to show the behavior.

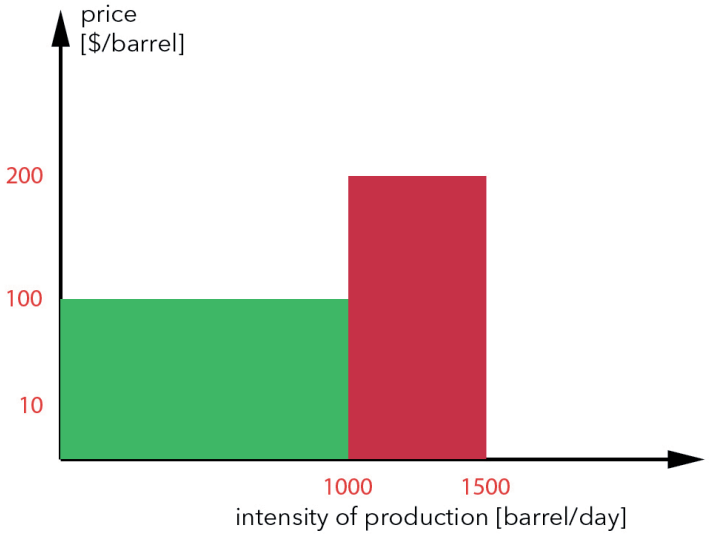



**Figure 4:** *Intensity of oil production vs. price (theoretical case).*

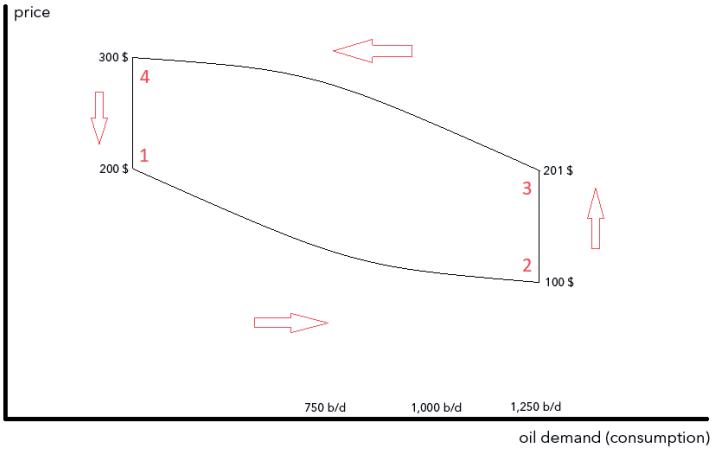



**Figure 5:** *Phase plot consumption vs. price (theoretical model).*

The phase plot should be like this because in our ideal world we expect that, if the oil price increases rapidly, the consumption decrease and, sooner or later, the society comes back to the previous range of intensity of extraction (i.e., within the green rectangle).

The main characteristic of the simple oil-price dynamical scheme here described is that there are two rapid movements along the cycle (rise and descent of the price: phases 4-1 and 2-3) and two slow (consumption that goes up and down, to adjust itself to the oil price: phases 1-2 and 3-4). The analogy between this characteristic of the oil

market and some dynamics in Ecology[6] is suggested at least by a model well studied[7], where we have three species in competition between them, following a variant of the Lotka-Volterra model:

1. **prey:** the American spruce, whose needles are the food of caterpillars of the species *Choristoneura Fumiferana* (this is the slow variable since the regeneration of the leaves - and not only - is a process that lasts several decades);
2. **predator:** the population of the caterpillars *Choristoneura Fumiferana*, considered able to vary rapidly (fast variable, since there are periodically observed demographic outbreaks of this species, considered a real scourge);
3. **"super-predator":** the population of birds, which eat the caterpillars, but do so at a rate that we can consider constant (identified as a "natural" rate of mortality of the caterpillars themselves) because this predator actually does not feed exclusively on these caterpillars. The demographic explosion of the latter, however, saturates the space for all prey (the needles of the spruce). In this sense, we will not take into account, in the following discussion, this variable.

In the construction of the ecological model, we start with a preliminary model in which the caterpillars' population N is the only variable, while the spruces' population S is introduced as an assigned parameter:

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{kS}\right) - \beta P \frac{N^2}{\eta^2 S^2 + N^2} \qquad \text{[eq. 2.1]}$$

We can define a range S- ≤ S ≤ S+ of values for S, for which the caterpillars' population could have three state of equilibrium (indicated in figure 6):

1. a "low" value of equilibrium N(S)-, asymptotically stable;
2. an intermediate value of equilibrium $N(S)_u$, unstable, and
3. a "high" value of equilibrium N(S)+, also asymptotically stable.

This notation recalls us that all equilibrium states are functions of the parameter S. Because of its instability, the equilibrium level $N(S)_u$ is inaccessible to the caterpillars' population, inasmuch as any variation of the population determines a rapid leaving from equilibrium and a fast convergence of the system towards N(S)- or N(S)+.

[6] For example Kar T.K., Batabyal A. (2010); Piltzy S.H. et al. (2017).
[7] Royama T. (1984); May R.M. (1977).

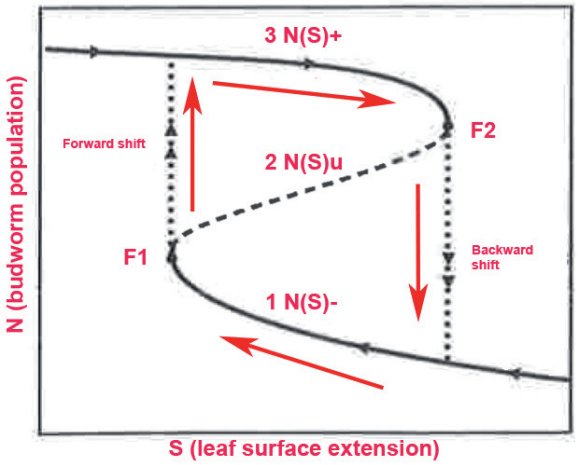



**Figure 6:** *Equilibria of the system*[8].

For S < S- only the stable equilibrium N(S)- is defined, while for S > S+ we have only the stable equilibrium at N(S)+. The preliminary model explains the outbreaks and collapses of caterpillars' population as imputable to slow variations imposed to the parameter S, which due to these variations "crosses" the critical values S- and S+. The variations of S are assumed "almost-static", i.e. so slow to ensure that almost instantly the population of caterpillars settles at the corresponding equilibrium value (the relaxation times at equilibrium of the N population of the caterpillars are considered much shorter than those of variation of the parameter S). The typical cycle of outbreaks and collapses of the caterpillars' population N is described as follow:

1. The process can start from a value S < S-, for which the caterpillars' population is equal or very close to the equilibrium value N-;
2. Then, we increase the value of the parameter S, corresponding to an increment of the spruce biomass. The parameter reaches and overtakes the critical value S- and still grows up until the critical value S+. In this interval, the caterpillars' population grows up but stands to the asymptotically stable equilibrium level N(S)-, because of all the possible fluctuations are lessened and reabsorbed. The compresence of the equilibrium $N(S)_u$ is not relevant, because of its instability;
3. The parameter S overtakes the critical value S+. The equilibrium N(S)- suddenly disappears, along with $N(S)_u$, and the population rapidly grows up to reach the "high" equilibrium value N(S)+, the only available and asymptotically stable. Further increments of the parameter S determine a further, but limited, increase of the caterpillars' population, in any case corresponding to the equilibrium value N(S)+;

[8] Personal elaboration of Scheffer M. (2009), p. 20.

4. The next step is reducing the parameter S, to simulate what actually happens: the overpopulation of caterpillars depletes the spruce biomass and determines its reduction. The parameter S reaches and overtakes the critical value S+, following its decrease until S-. The caterpillars' population slowly decreases, maintaining itself, as long as possible, close to the asymptotically stable equilibrium point N(S)+. Also in this part of the cycle the intermediate equilibrium $N(S)_u$, even if defined, does not play any role because of its instability;
5. The last step: the parameter S finally passes below the critical value S-. This results in the destruction of the equilibrium N(S)+, as well as that of $N(S)_u$, with a consequent rapid collapse of the caterpillar population to the only available equilibrium value N(S)-. Any further decrease in S leads to a reduction in the population of the caterpillars, which however remains at the equilibrium value N(S)-;
6. Now the caterpillars' population is at the minimum level, the spruces biomass can start to grow up again, so that the parameter S grows up in turn and the cycle restarts.

figure 7.1

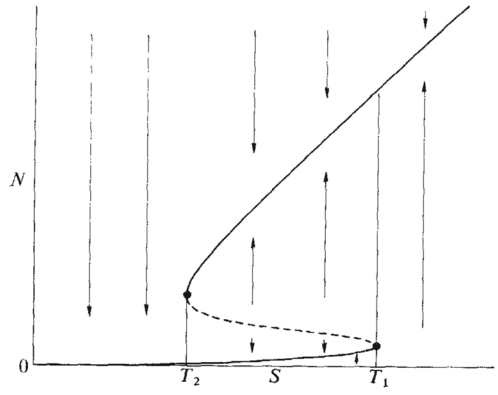



figure 7.2

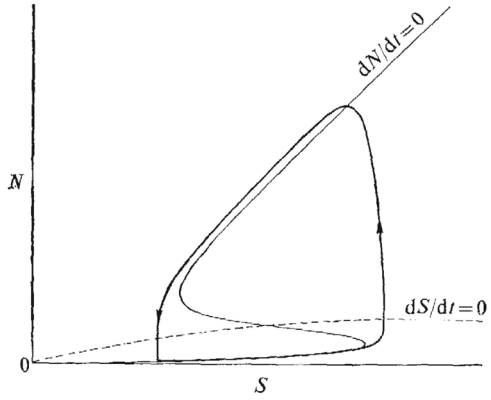



**Figure 7 - 7.1:** *The equilibrium budworm population. N, shown as a function of the average leaf area per tree, S.* **7.2:** *The (solid dN/dt=0) equilibrium curve for budworms. N, as a function of foliage S (as indicated in 7.1, where the dashed line is the non-equilibrium range* $N(S)_u$*)*[9].

The previous model with a variable (N) and a parameter (S) suggests a more complex two-variable model in which the population of caterpillars and the biomass of spruces are considered both as dynamic variables, in mutual interaction. In the further differential equation that governs the dynamics of S the characteristic constant parameters are chosen to ensure that the variation of S over time remains relatively slow. In this way, we can consider that the trends observed in the preliminary model with a

[9] May R.M. (1977), picture 6 and 7 respectively.

single variable persist also in the new two-variable model, giving rise to a stable limit cycle characterized by two rapid growth and decrease phases of caterpillars' population N. These rapid variations of budworm population alternate with two relatively slow growth and decrease phases of the same population, while the biomass of spruces varies always rather slowly, both increasing and decreasing, throughout the cycle.

The model was originally developed in Canada to describe infestations observed there. The Canadians had observed that the spruce budworm population underwent irruptions approximately every 40 years. For unknown reasons, the budworm population would explode, devastating the pine forest, and then return to their previous manageable levels. The loss of timber represented a significant cost to the Canadian wood products industry and various management techniques, pesticide application, for example, were tried without success.

As it is often the case in real-world modeling, the models became simpler as the researchers learned which processes were critical to the dynamics of the system and which could be removed from the model without seriously affecting its usefulness. The simplest of these models is a single species model, measuring only spruce budworm populations. The differential equation is in this case:

$$\frac{dN}{dt} = \frac{r * N * \left(1 - \frac{N}{K}\right) - (\beta * P * N^2)}{N_0 * N_0 + N^2} \qquad \text{[eq. 2.2]}$$

Where N, the spruce budworm population, is the only variable in the problem.

The parameters in the problem are:

- r, the natural growth rate, as in the logistic model;
- K, the carrying capacity, as in the logistic model;
- β is a measure of predation efficiency. If birds are good at catching spruce budworms, this number will be larger than if birds often miss the budworm they are attacking;
- P is the bird population, considered a constant in this model;
- $N_0$ is called the switching value, more on this soon.

This real-world model is simply the logistic model with one additional term, which is designed to incorporate the effects of predation. The predation term deserves some attention. The parameter β represents the predation efficiency of birds, while P represents the number of birds, and the remaining term:

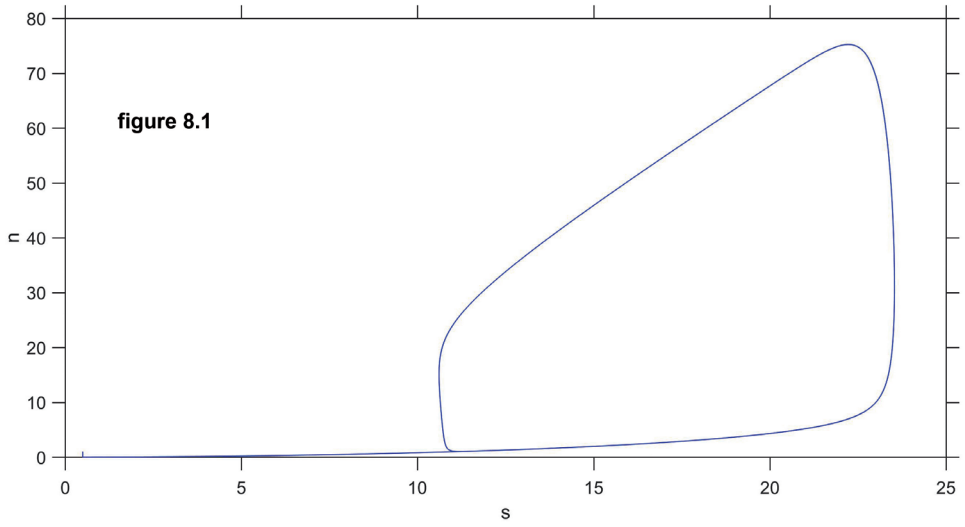
$$\frac{N^2}{N_0 * N_0 + N^2}$$

is called predation function and it measures how intensively the birds will select spruce budworms for predation. The idea is that birds are lazy; they will go where food density is high allowing them to consume much while expending minimal energy. If the spruce budworm density is low, birds will opt for some other prey, which most likely lives in other parts of the trees.

For example, if birds decide that beetles are abundant, they will congregate around tree trunks and branches where beetles can be found, leaving the spruce budworms unmolested. On the other hand, once the budworm population increases the birds will leave the beetle habitat behind and begin focusing on the easier prey, budworms in this scenario. Thus predation on budworms exhibits this switching phenomenon, and it is this behavior which is represented by the predation function. The importance of the parameter $N_0$, known as the switching value, is that when $N = N_0$ the value of the predation function is exactly one-half. This indicates the population at which predators begin showing increased interest in harvesting budworms.

Through observation it had been observed that two of the model parameters, No and K, are directly dependent on the average leaf surface area per tree. Letting S be the average leaf surface area, then $N_0 = 0.5 \times S$ and $K = 4 \times S$.

This relationship between leaf area and $N_0$ and K allows us to investigate the effect of growing trees on the budworm population.



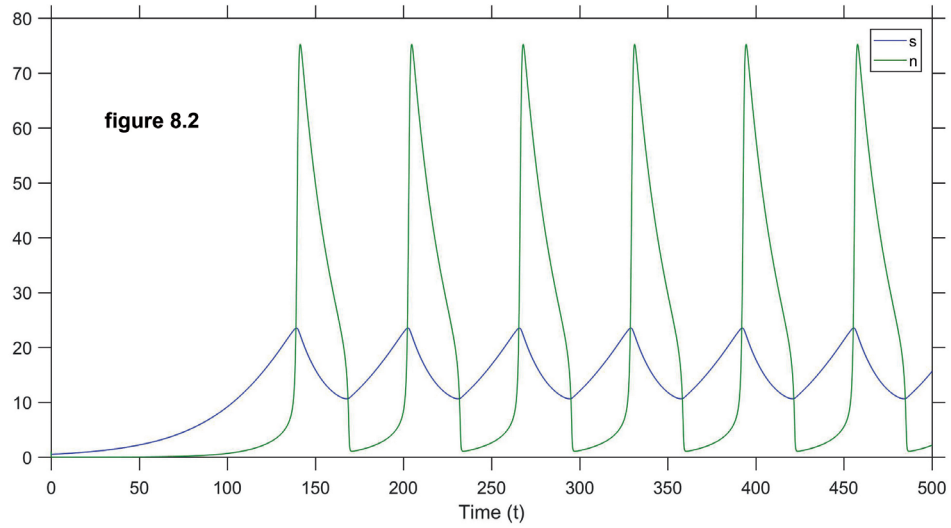



**Figure 8 - 8.1 (previous page):** *The result of a Matlab simulation for the phase plot caterpillars' population vs. spruces foliage and* **(8.2)** *the same values vs. time.*

### *3.1 The transition to Economics*

The shift from Ecology to the Economy (oil price-EROI cycle) is suggested by the following qualitative considerations:

1. The price of oil is potentially able to undergo very rapid changes, being linked to the delicate balance between supply and demand. On the contrary, EROI by its own definition appears as a parameter that changes slowly because its decrease naturally derives from the exploitation of deposits, while its increase can be obtained through the implementation of cultivation technologies already available (at best), the search for new deposits, or the improvement of the technologies themselves, operations that require time and significant investments.
2. A very low level of EROI can be associated with a rapid increase in average prices, due to the difficulty of extracting the resource at low energy costs; on the other hand, a very high EROI will favor high levels of production and a general decline in the price of the resource.

By introducing the variables E=EROI=1/S and N=price, the equations can be rewritten as follows:

$$\begin{cases} \dfrac{dE}{dt} = \rho\left(\dfrac{1}{S_{max}} - E\right) + \varepsilon N E^2 \\ \dfrac{dN}{dt} = rN\left(1 - \dfrac{1}{k}NE\right) - \beta P \dfrac{N^2}{\eta^2/E^2 + N^2} \end{cases}$$

[eq. 2.3a]

[eq. 2.3b]

Putting E in abscissas and N in ordinates in the phase plane, with appropriate choices of the constant parameters we obtain the following typical limit cycle:

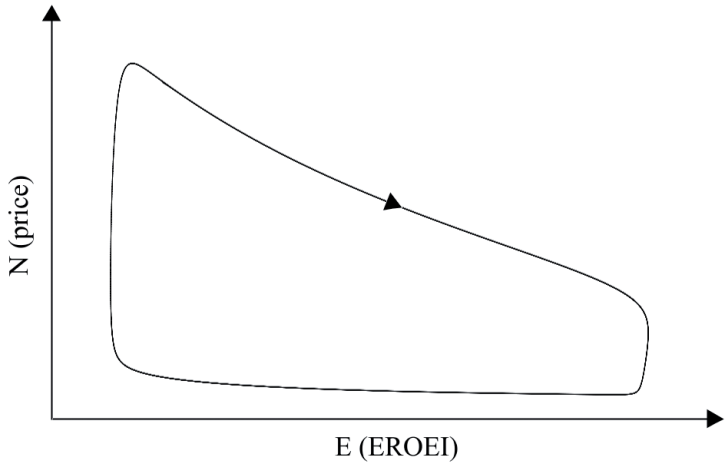



**Figure 9:** *Limit cycle for N=price and E=EROI=1/S.*

As time goes by, the cycle is covered clockwise, with the right and left vertical sections corresponding to a sudden drop in the average price for high values of the EROI and a rapid rise in prices when the EROI reaches a minimum critical value, respectively. The inclined traits show an approximately hyperbolic trend: the lower one shows a slowly increase of the average prices in response to a the slow decrease of the EROI, and could correspond to the model proposed by Court and Fizaine[10], while the upper one describes a more decisive, but still relatively slow decrease of the mean price with the slow increasing of the EROI.

The interesting aspect of the model is that the price is not described as a function of the EROI, because two different price levels correspond to the same value of EROI, according to the historical phase of the economic cycle where the system is placed.

Basically, we are faced with two zones of stability, one with a high content and one with a low content of "predators" (price), which are alternately reached. The reason why the quantities were chosen is that, in the oil model, the quantity that varies faster is the price, while both the total production and the EROI (which depends on technology and investments) are quantities with too many constraints to be able to vary quickly. EROI does not succeed because of the technical conditions of production, while production does because of the constant energy hunger.

[10] Court V., Fizaine F. (2017).

## 4. The model implementation with Vensim

The implementation of the caterpillars-spruce model has undergone a further transformation and it was inserted into a Vensim model[11].

As we can see in figure 10, the phase-plot – which, we remember, in the abscissa has the values of the extension of leaf surface and in the ordinate, the population of the caterpillars – is represented in the model by two rectangles indicating the stocks, while the "hourglasses" indicate flows.

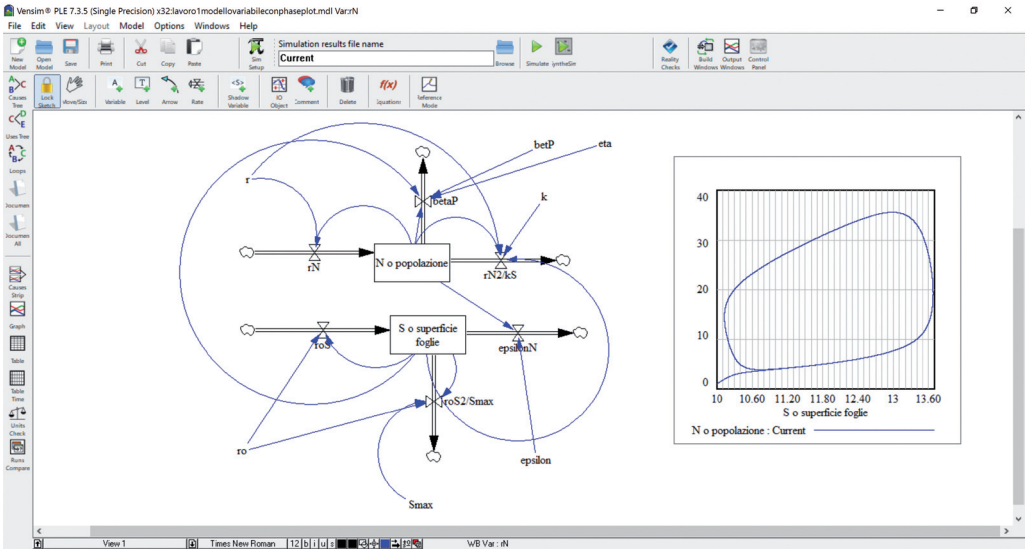



**Figure 10:** *The model caterpillars-spruce implemented in Vensim.*

The interaction between these two variables accounts for the model. In particular, following what is indicated by the differential equations, the extension of leaf surface is governed by the following equation:

$$\rho * S - \mathcal{E} * N - \frac{\rho * S^2}{S_{max}} \qquad \text{[eq. 2.4]}$$

while the population of the caterpillars from this one:

$$\beta * P + r * N - \frac{r * N^2}{k * S} \qquad \text{[eq. 2.5]}$$

In figure 11 the tendency along the time.

[11] Vensim is a software specialized in modeling in systems dynamics.

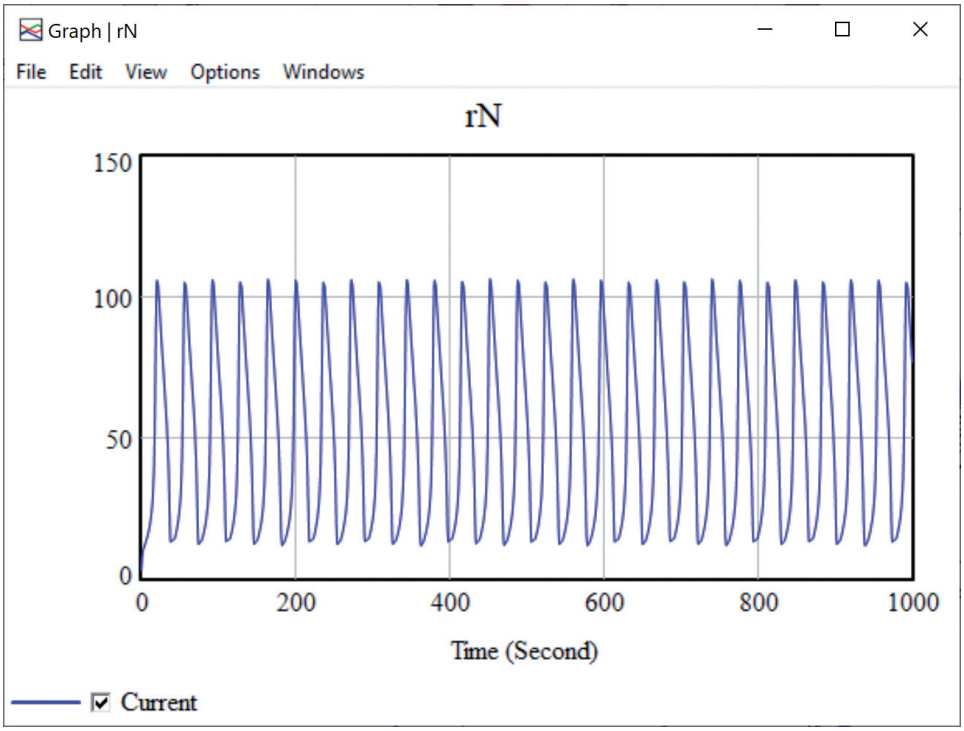



**Figure 11:** *The caterpillars' population along the time, as we have seen with Matlab representation.*

## 5. Some other considerations about oil market: the decline of the above-ground factors

Court and Fizaine (2017) have proposed a general method for the calculation of the EROI of fossil fuels relating the EROI to the price of the considered commodity (oil, gas or coal) and other economic variables, namely Energy Intensity (EI) and the Monetary Return on Investment (MROI). In the Court and Fizaine method, the EROI is calculated as:

$$EROI_i = \frac{MROI_i}{P_i * EI_i} \qquad \text{[eq. 2.6]}$$

where the index i refers to oil, gas, and coal. MROI is the monetary return on investment of the i sector and EI the energy intensity of the same sector[12]. Some assump-

[12] Energy intensity is a measure of the energy inefficiency of an economy. It is an economic parameter and it is calculated as units of energy per unit of GDP. Monetary return on Investment (MROI) or, (>>>)

tion and simplification are made in the Court and Fizaine model: first, the MROI is taken as that of the industrial sector in the USA. Different methods are used for its calculation and the conclusion is that MROI has little effect on the EROI. The EI is also taken as the average world energy intensity[13]. This factor is much more important in determining the final value of EROI. The authors propose to consider the ratio between MROI and Price as a proxy of the monetary costs of extraction. The price of a commodity is in fact determined by a large number of above ground factors and not only by its extraction costs.

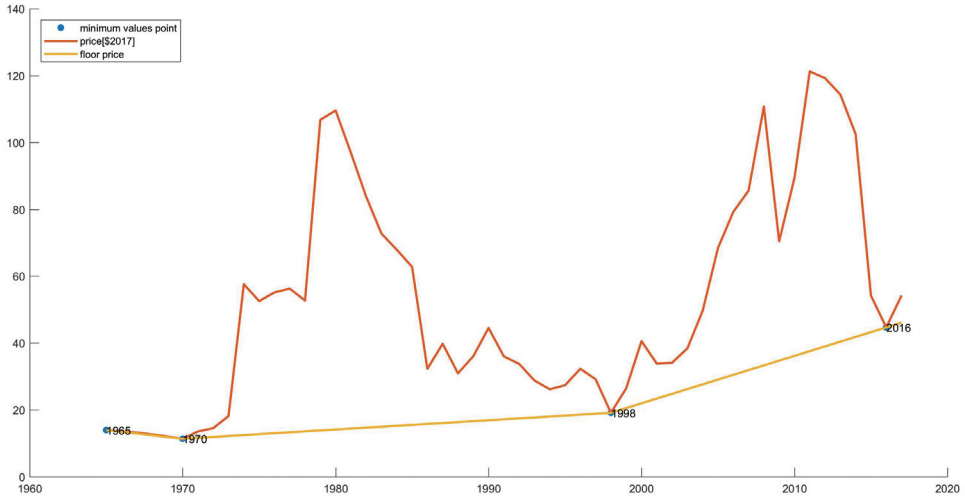



**Figure 12:** *Price (in $2017/barrel) from 1965- 2017 (red). Floor price (yellow).*

Observing the variation of the price of oil from 1965 to 2017 (given in figure 12) two large cycles can be identified: the first one starts with the Yom Kippur war in 1973, and ends in the 80s; the second one starts at the beginning of the XXI century, with the entrance of China in the WTO, and ends up in 2016 with the sudden decline of the price of the barrel. Attributing most of the increase in price during the two cycles to above ground effects; political, geostrategic, financial etc., one can identify a

(<<<) more simply Return on Investment (ROI), is a performance measure used to evaluate the efficiency of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio. The return on investment formula:

ROI = (Gain from Investment - Cost of Investment) / Cost of Investment

In the above formula, "Gain from Investment" refers to the proceeds obtained from the sale of the investment of interest.

[13] It depends on which economy we consider to make calculation.

floor of the price variation as the "minimum price" necessary in the long run to make remunerative the extracting activity of the petroleum enterprises. Such minimum is tentatively (and somehow arbitrarily) identified by the yellow line in figure 12. I infer that such minimum price corresponds to an MROI = 1 (breakeven price) and, with the previous formula of EROI in Court and Fizaine model, we have:

$$P_{min} = \frac{1}{EROI * EI} \qquad \text{[eq. 2.7]}$$

This minimum price could be attributed to "below ground effects" only. Using these $P_{min}$ values we can calculate the upper boundary of oil's EROI. EI is given by the ratio between oil consumption (BP statistical review) and World GDP (IMF) in the 1965- 2017 historical series. The EROI values are shown in Figure 13.

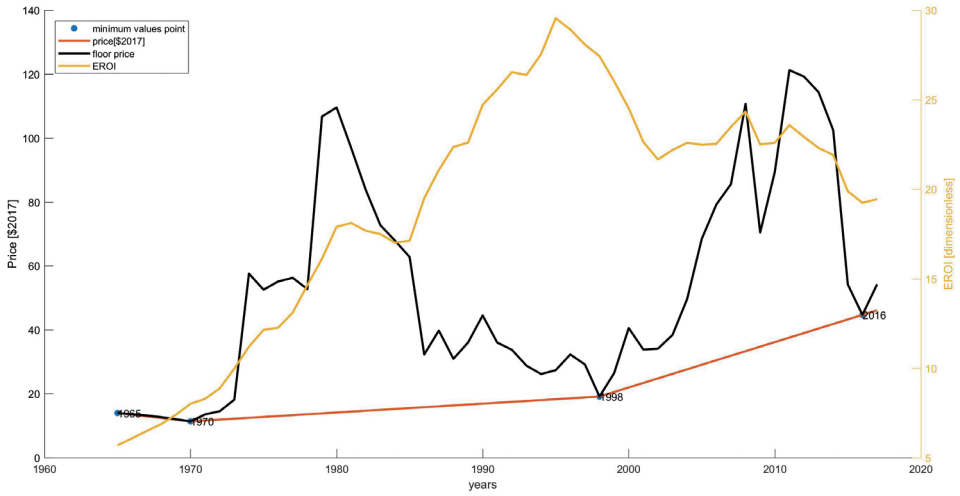



**Figure 13:** *Price (in $2017/barrel) from 1965- 2017, floor price and EROI values.*

It is also possible to conceive a real fit for the background price. In this case, the values are slightly different, as we can see in picture 14.

The interpretation of these results is that the prevalence of above-ground factors decline with time in the observed historical series and geophysical factors become more important in time. The increase of Pmin was historically compensated by the decline of EI. But in the long run, $P_{min}$ is expected to increase as EROI decline and EI flattens as an effect of the technological maturity of the sector and of the gradual and exponential increase of the physical factors affecting the costs of extraction and, therefore, the market price of oil.

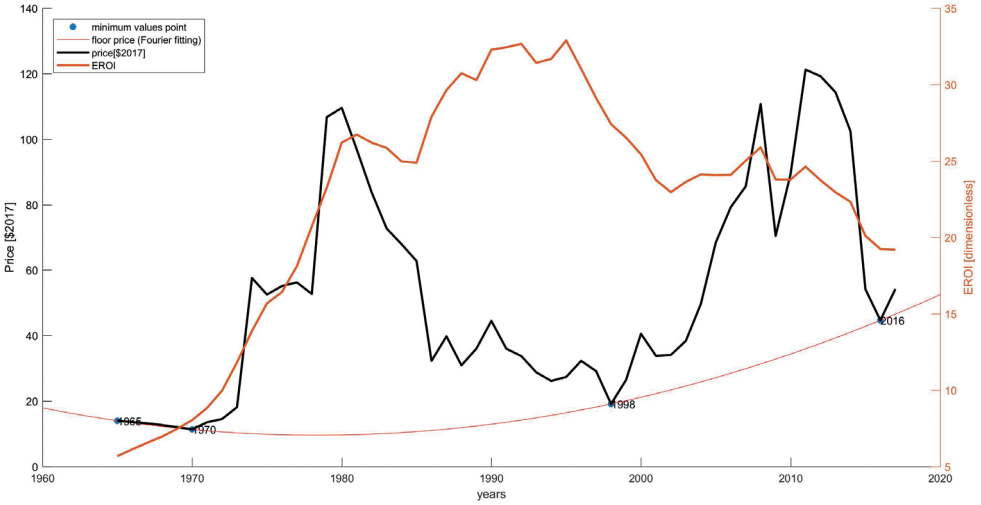



**Figure 14:** *Price (in $2017/barrel) from 1965- 2017, floor price and EROI values with Fourier fitting method.*

# Chapter 3.
# Dissemination and outreach

## 1. Introduction

The dissemination of ideas, concepts, research projects and so forth, plays an increasingly important role. For example, in the European projecting, there are guidelines on this aspect to present a proposal[1], even if measuring the results could be not so simple[2]. Recently, also at the World Economic Forum in Davos (Switzerland), the weight of the scientific communication was awarded with the Crystal prize assigned to Sir David Attenborough, broadcaster and naturalist[3].

In this scenario, the main goal of the dissemination of this project is talking about resource depletion. An attempt consisted in explaining the dynamics of the peak, illustrated by Hubbert[4], but this concept, apparently simple, is actually quite sneaky and the best proof of that is the astonished faces of people whom this explanation have been given to. Due to this substantial failure, a second attempt was made by talking about the peak of discoveries: if the trend in discoveries is a peak, probably the resource exploitation should show the same trend too, as we can see in figure 1.

[1] http://ec.europa.eu/research/participants/docs/h2020-funding-guide/grants/grant-management/dissemination-of-results_en.htm

[2] There are several indicators that can be considered: (1) the time spent; (2) the allocated budget (expenses for translations, publications, dissemination events, etc.); (3) the results produced (number of publications, number of conferences, number of books, etc.); (4) the amount of impact (the number of people reached, number of advertising spots transmitted, number of leaflets distributed, number of web accesses to the site, number of citations obtained, etc.), and so on. It is clear that there is not just one way of measuring the degree of information circulation (that which is used for dissemination), just as there is no relevance of one to the other. Much depends on the subject matter, the content of the dissemination and the target (even more than one at times) to which it is addressed.

[3] *David Attenborough: 'The Garden of Eden is no more'. Read his Davos speech in full*, available at: https://www.weforum.org/agenda/2019/01/david-attenborough-transcript-from-crystal-award-speech/

[4] Hubbert M. K. (1956).

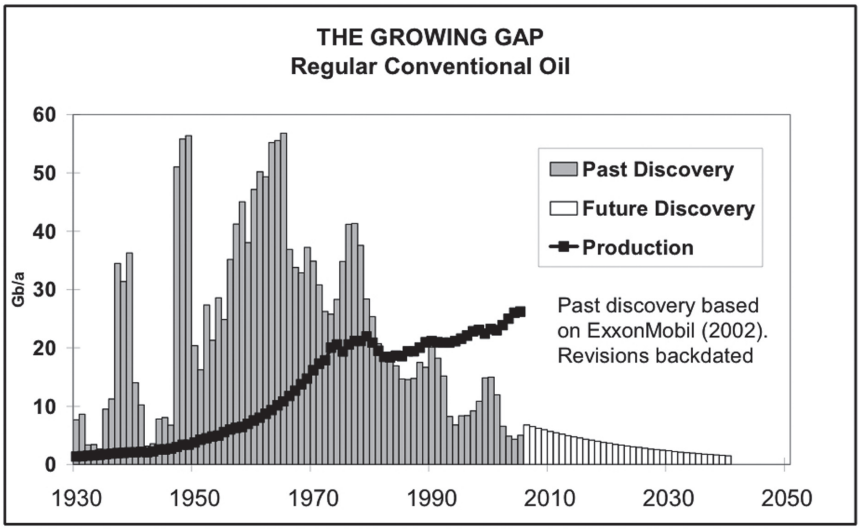



**Figure 1:** *Colin Campbell's graph on the discoveries peak. Slightly different it appeared in Campbell (2002), p. 198.*

Campbell's original work is completed by the Bentley book[5], in which it is possible to see, as examples, some different "philosophies" of wells exploitation, in figure 2:

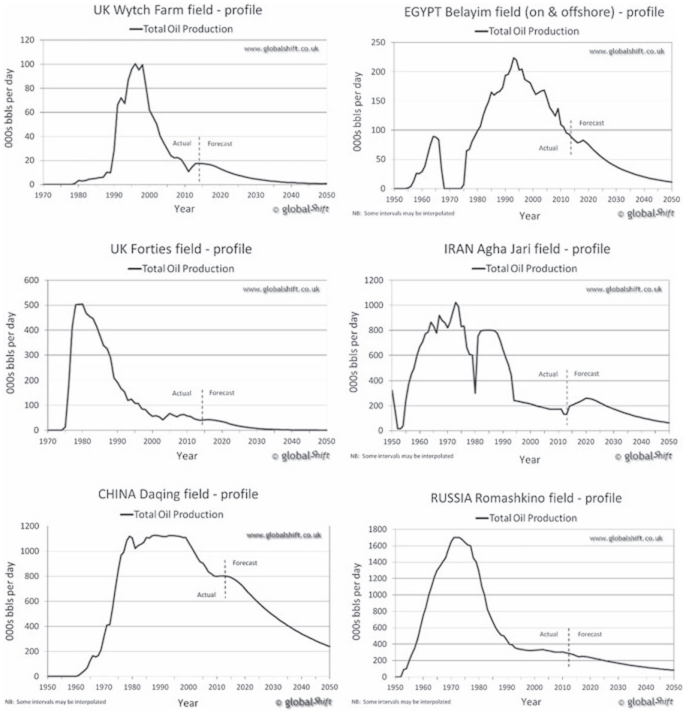



**Figure 2:** *Typical oil field production time profiles, Bentley (2016), p. 10.*

[5] Bentley R. W. (2016).

By looking at these various pictures it is quite evident the differences among them about the intensity of exploitation and their trend for which it could be possible hazard political hypothesis. The top-left picture, the middle-left and the bottom-right one belong to Western countries (except Russia, but probably after the middle Eighties it could be assimilated to the Western ones) and the intensity of exploitation is very fast, following the Hubbert's peak and, in some cases (the bottom-right), in the descent part, the Seneca cliff[6].

In other cases (bottom-left and middle-right pictures), the descent is quite smooth and the political order for those countries is not the capitalism, so probably the efficiency of extraction and the typical market supply-demand is not the same encountered in a free market regime.

But obviously, in these cases, it could be even more difficult to try to explain, even if, in the meanwhile, also the last Energy Outlook report wrote: «Global conventional crude oil production peaked in 2008 at 69.5 mb/d and has since fallen by around 2.5 mb/d. In the New Policies Scenario, it drops by a further 3 mb/d between 2017 and 2040, and its share in the global oil supply mix falls steadily from 72% today to 62% in 2040.»[7].

Therefore, the project was turned back to the mathematical basis of Hubbert's theory of peak. It should be helpful to refer to a concept like the logistic function and its derivative because they find applications in a wide range of fields, including artificial neural networks, biology (especially ecology), biomathematics, chemistry, demography, economics, geoscience, mathematics and, last but not least, the explanation of the peak oil and, generally speaking, the resources depletion. The function is mathematically described by the general formula:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \qquad \text{[eq. 3.1]}$$

where the parameters within the formula mean:

- $e$ = the natural logarithm base (also known as Euler's number),
- $x_0$ = the $x$-value of the sigmoid's midpoint,

[6] The Seneca cliff was theorized by prof. Ugo Bardi and it is used to describe the nature of the descent part of the Hubbert's peak. Indeed, following the thinking of the ancient Roman philosopher Lucius Annaeus Seneca who wrote to his friend Lucilius noting that "growth is slow, but ruin is rapid", Bardi uses the Seneca's observation as a key element we need to understand the developments of what we now call the "science of complexity". For a short presentation on the web: http://thesenecatrap.blogspot.com/ or, in bibliography see Bardi U. (2017).

[7] IEA (2018), p. 45.

- $L$ = the curve's maximum value, and
- $k$ = the logistic growth rate or steepness of the curve.

It is often assumed, for simplicity, $x_0 = 0$, L = 1 and k = 1, so that eq. 3.1 becomes:

$$f(x) = \frac{1}{1 + e^{-x}} \qquad \text{[eq. 3.2]}$$

and its derivative is:

$$f'(x) = \frac{e^x}{(1 + e^x)^2} \qquad \text{[eq. 3.3]}$$

Both equations [3.2, 3.3] are shown in figure 3:

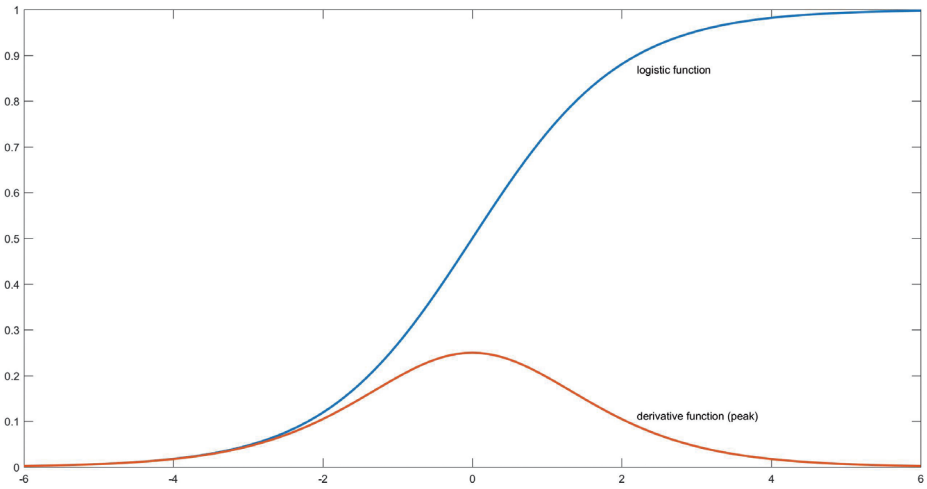



**Figure 3:** *Logistic function and its derivative (peak) with x values between -6 and 6.*

As already mentioned, despite the simplicity of this concept, it is quite difficult to understand it for non-expert people. In which way could it be possible to explain and make it more understandable? The idea was to get back to a paper written by prof. Ugo Bardi[8] about a game. The aim of the game – called Hubbert's Peak game – is to let common people, especially school kids, to experience the resources depletion.

[8] Bardi U. (2016).

## 2. Playing the Hubbert's Peak game

The game of Hubbert's Peak is an educational activity that explains how non-renewable resources are used up and how they could be replaced by renewable ones. The non-renewable resource par excellence is oil, represented in the game by the black chips contained in a bag. In the bag there are black tokens (oil fields) and white tokens (empty extraction). When a black token is extracted, drilling has been successful, when a white one is drawn, drilling has failed and the token is returned to the bag. Each player has four containers numbered 1 to 4. The tokens are placed initially in the first container and then moved progressively at each turn: after being placed in the fourth container, they are removed: this indicates the duration in time of a deposit and its production output.

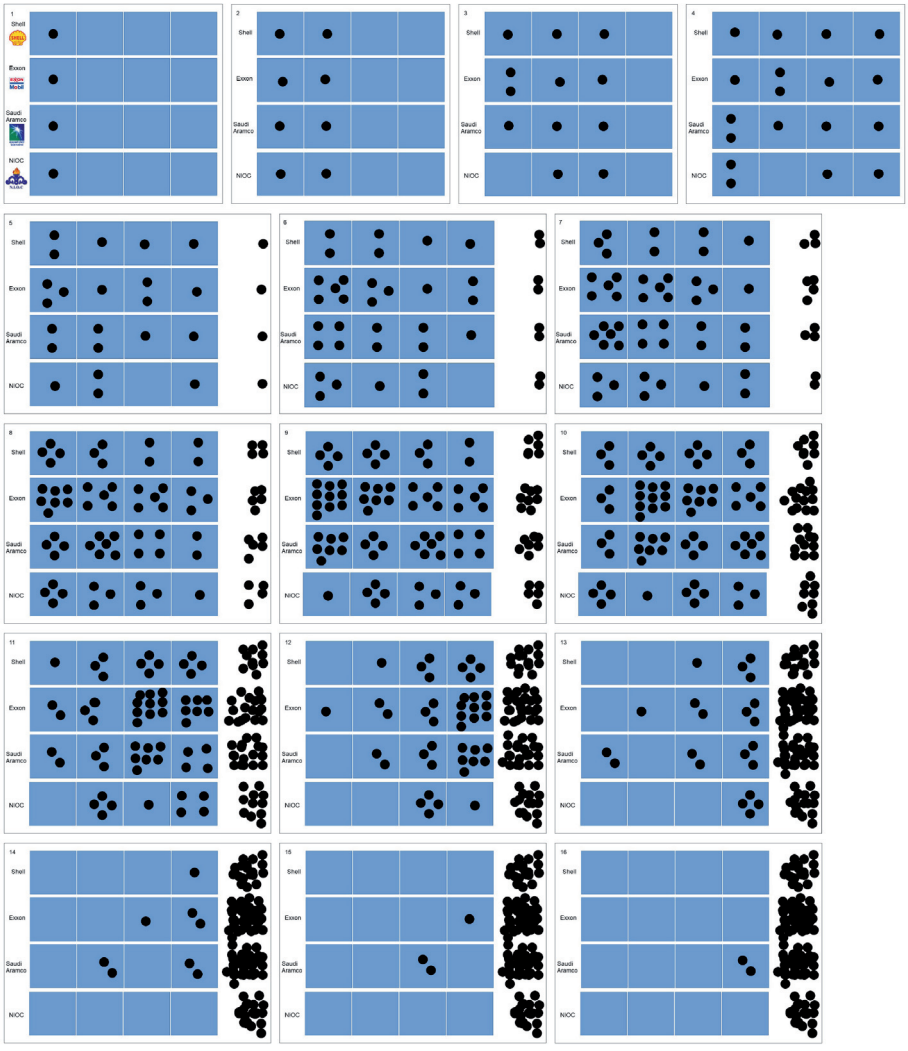



**Figure 4:** *The sequence of a possible match with four players.*

### *2.1 First release*

In the first version of the game, «each black counter in play is supposed to generate one "capital unit" that can be invested in order to explore for more resources. One capital unit is supposed to generate one investment unit that allows the extraction of a single counter from the box. This mechanism ensures a gradual depletion of the resource, which becomes more and more difficult to find as the game progresses. The game requires also a "production sheet" on which the extracted black counters are placed, and a record sheet where players keep track of the progress of the game»[9].

Figure 5 shows the result of a game simulation with two players, 200 black and 80 white tokens. We can see how player A had a slight advantage over B because he always draws first from the bag.

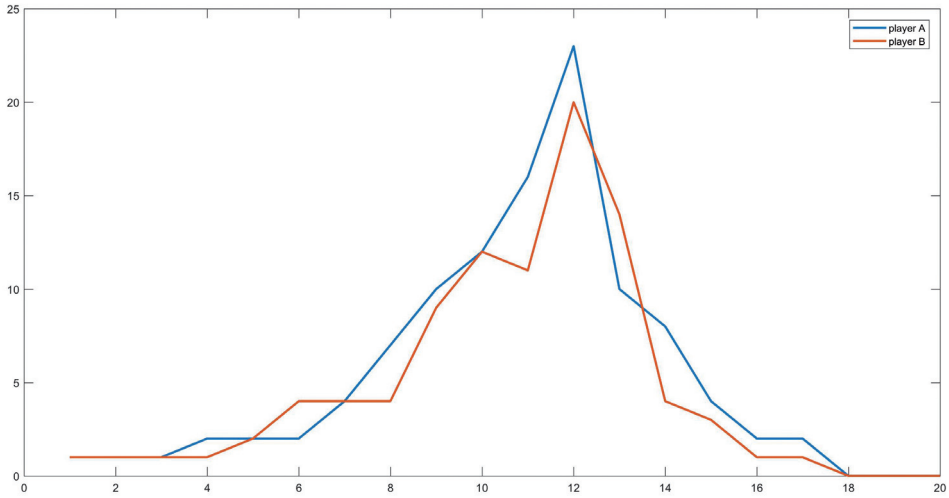



**Figure 5:** *A game simulation with two players, 200 black and 80 white tokens.*

### *2.2 Second release: the introduction of economy*

Luca Pardi and I have fulfilled a "fine tuning" of the game. First of all, the order in which the players draw the tokens from the bag at each turn is chosen by casting a die, to avoid the advantage to be always one player the first for each turn.

At the beginning of the activity, each player enjoys a certain credit in the bank, by which he can finance a certain number of drillings; each drilling corresponds to a token drawn from the bag. Each token gives the player 50 monetary units (MU) per turn.

[9] *Ibid.*, p. 7.

The gain received at each turn can be invested in new drillings: each drilling costs 30 MU. Each player has an economic budget that includes costs, revenues, taxes, and profits.

One technical improvement consists in a little software script[10] of randomization useful to avoid the great number of physical token extractions when the game is more or less "around the peak" and the players are entitled to make a large number of them.

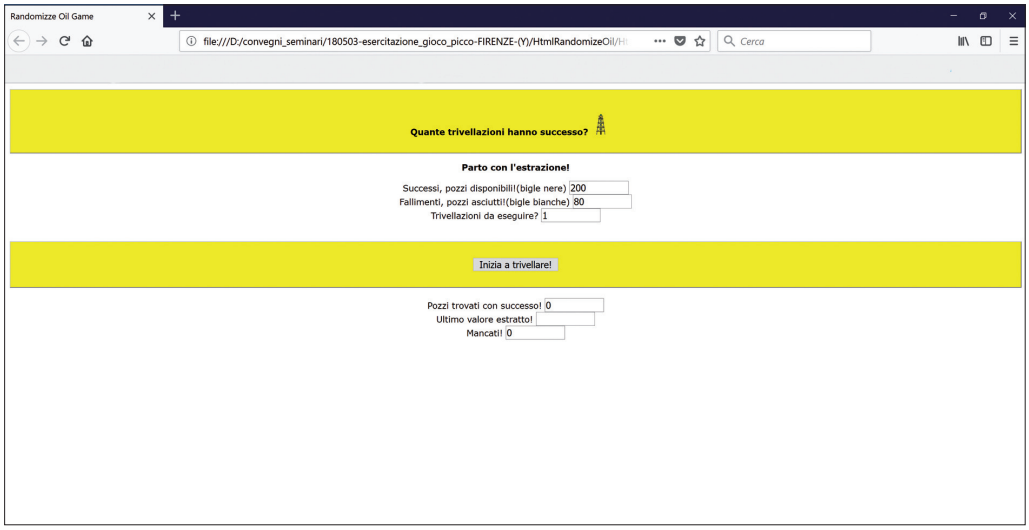



**Figure 6:** *The "randomizator" software screenshot.*

### *2.3 Third release: the introduction of renewable resources*

In addition to the economic dimension, we have introduced the operating costs and the opportunity to invest in photovoltaic plants - respectively 10 and 5 MU for a well and a renewable plant. Taxes are 20% on profits (zero if the player is at a loss). The player has the possibility to take out debts to operate, debts that must be repaid within 4 turns. The players can choose whether to invest more money in extractions or in photovoltaic systems, knowing that they can accumulate profits from one shift to another.

The renewable plants cost 180 MU (6 times more than an extraction plant) but they never go out of the game in this release. In this way, the game appears more similar – for its educational purpose – to an energy transition project, rather than looking only at the resources exploitation. However, the goal of the game is always to accumulate wealth and facilities, both traditional and photovoltaic.

[10] Substantially a java script and html.

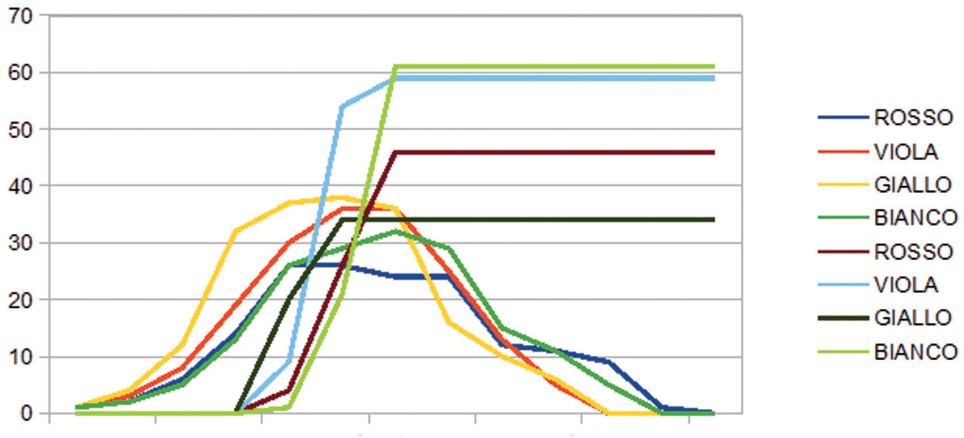



**Figure 7:** *A match with 4 players the Hubbert's peak and the transition to the renewables.*

### *2.4 Further developments*

The game was played in several contexts: the Italian night of researchers in Pisa (with Luca Pardi) and, at the same time, in Trento (with Claudio Della Volpe and me) in 2017; a session was played by Luca Pardi and me with students of the degree course in Economic Development, International Cooperation and Conflict Management, University of Florence, in 2018.

One of the main drawbacks of the game is the time: playing a match requires a minimum one hour or one hour and a half. In public contexts – like where we have played the game – rarely people have the will to stay for a long time to rolling dices or to fishing tokens in a bag, with the aim to discover the resource depletion dynamics or make an energy transition.

For this reason – to speed up the game – we created the "randomizator", to prevent people from pulling the tokens 30 times in a row. This is the first step for further developments: now we have calculations embedded in a spreadsheet and probably they can move to some other software scripts and make the game itself more "virtual" and perhaps more "viral". The final point could be the creation of an app for smartphones and, in this way, play without staying all players in the same place[11].

From a scientific point of view, we have collected all matches with the aim to analyze them and look in which way people conduct (and interpret) their role using the money, making investments and so on.

[11] In this direction, I have created also a web page (in Italian) to present the game: https://sites.google.com/g.unitn.it/gioco-del-picco/home

## 3. Project dissemination: the elusive concept of energy

The concept of energy is quite elusive and to improve the awareness about this topic Richard Buckminster Fuller has introduced the concept of "energy slave", in the first part of the Forties[12]. This can be used to understand how lucky we are to live in a world energized by intrinsically cheap and abundant resources, much more powerful than human or animal power. A healthy person can generate a power of 800 W for a short time (e.g., running up on a staircase), but during a continuous day of work he/she cannot develop more than 80 W.

We can make examples to see how this amount of power compares with that we employ in our normal, everyday life. When we look at a football game on TV, we mobilize a power of 120 W for 1.5 hours[13]. If we could not plug our TV set to the electricity distribution system, we would need one and a half human slaves pedaling for us all the time of the football game to produce the electricity needed. For operating a washing machine (800 W) by human energy, about 10 slaves would be needed. Electrical heating of a small room (2.5 kW) corresponds to the work of over 30 human slaves. A small European green cutter (3.5 kW) consumes in one hour the energy produced in an entire working day by more than four human slaves.

A medium-sized car (engine power 80 kW) running on a highway consumes an amount of energy equivalent to that produced by the work of 1000 human slaves. Not even a Roman Emperor had so many slaves available to draw his cart. Nowadays, we can assemble and immediately use such a great number of energy slaves simply by turning the key of our car. A Boeing 747-400 needs 80 MW to take off, which means that as many as one million human slaves should be employed to raise it by human muscular work.

But who powers our energy slaves? Mostly, fossil fuels. The power of a big coal electric plant (800 MW) corresponds to that of about 10 million human slaves. The 100 GW of electric power installed in Italy corresponds to the power of 1.3 billion human slaves. On average, each modern Italian citizen has as many as 55 energy slaves at service 24/7, all year long. In the US, each citizen is served by not less than 135 energy slaves. On growing, we have been taught to command these unseen and maybe even unappre-

[12] Someone – like Balzani, Armaroli (2011) – wrote 1944, but the corresponding voice on Wikipedia (*Energy slave*) says: «The term was first used by R. Buckminster Fuller in the caption of an illustration for the cover of the February 1940 issue of Fortune Magazine, entitled "World Energy"». One of the most comprehensive books on this argument remains Smil (1994).

[13] This experiment was done to improve the awareness of kids at school, converting at least one exercise bike with a dynamo to generate current and try to watch a football match on tv, generating the necessary power by pedaling.

ciated energy slaves. They are always ready to assemble and serve if we only have money to pay their incredibly low salaries. One liter of gasoline costs about euros 0.5 (before tax) and has an energy content of 12.9 kWh. The energy produced by a full day's work of a human slave is 800 Wh. Therefore, the energy produced by one liter of gasoline corresponds to that produced by about 16 human slaves whose one – day salary should be as low as euros 0.03 to compete with the cost of the gasoline – based energy slaves.

Finally, right on "energy slaves", Stuart McMillen, a young Australian cartoonist and science communicator, wrote a comic on the Fuller's biography, inside a wider project entitled "Thermoeconomics"[14], while my personal contribution is found in the list described in appendix 3 and consist in the publication of articles in Italian non-specialized magazines. A list of these articles and the involvement in the scientific committees of a couple of magazines are available in appendix 3.

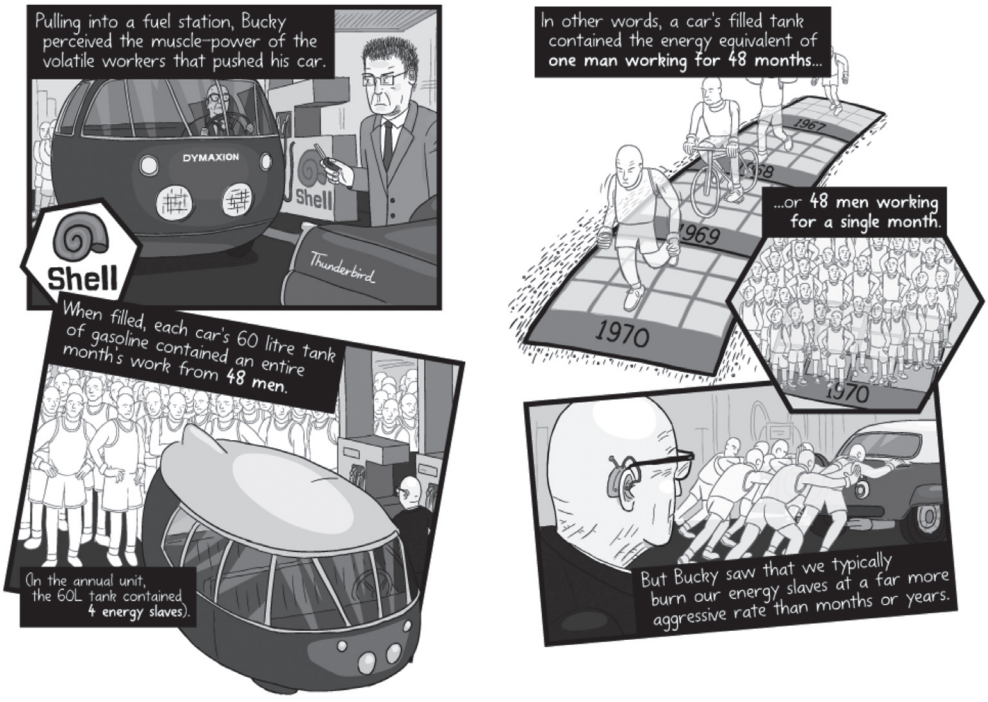



**Figure 8:** *A screenshot of Stuart McMillen' "Energy Slaves" comic. All right reserved.*

[14] See the web page: http://www.stuartmcmillen.com/comic/energy-slaves/

# Conclusions

Probably every research has a starting point but it is endless. In particular, for the first part – the calculation of the EROI of the large oil companies:

1. As we have seen in the previous pages, nowadays fossil fuels send the world forward and, in some regions (Middle East), the export of oil and gas constitutes almost the whole GDP of those countries. This means, generally speaking, looking for sensitive data, difficult to find, even if the academic research has no specific interest – and this is often the major challenge.
2. The other major challenging item is to find out a way, a method to achieve a goal by using the available data[1] – in a part of this research: calculating the EROI of oil companies (called $EROI_{INC}$).
3. Finally, yet importantly there is the publication in a scientific journal, a not simple path, but fundamental to a public validation of the research, via peer-to-peer review method.

In particular, the peer-review process allowed us to refine and improve the method used for the determination of EROI. Many of the reviewers' objections have led to a rethinking and deepening of elements that in the early draft of the article were clear only to us and not to those who were reading the text for the first time.

One of them is referred to the economic issue and the specification of precise choice: using revenues instead of other economic parameters as EBIT (earnings before interest and taxes) or EBITDA (earnings before interest and taxes, depreciation, and amortization).

The aim of relating revenues with production (and not only EROI) was simply that of highlighting any relationship among oil companies that make mainly extraction compared with those that deal with refining and among public companies vs. private.

[1] In this case "available" means "public", findable on the web and, above all, declared by the companies themselves, without paying expensive databases that obviously exist.

Another issue is about the EROI. The $CO_2$ emissions are a proxy, and they create the possibility for distortions that must be corrected. The problem extends to natural and oil products: gas has a significantly higher Higher Heating Value (HHV) per C atom than oil has, so just counting the $CO_2$ without counting the relative contribution of the company products (gas and oil) to $CO_2$ leads to a mis-estimation of the energy out the proxy.

We, therefore, had to determine the percentage of oil companies' emissions related to oil and gas production and then redo the calculations to determine more precise EROI values, even if only slightly different from the previous ones.

In any case, even with some adjustments, the method seems to work and has the undoubted advantage of being "universal" (if emission and production data are available) and, above all, referring to official data supplied by the oil companies themselves. Further investigations should be devoted in the years to analyze the time evolution of the $EROI_{INC}$ and also to develop more precise and easy to evaluate corrections with the aim to compare the standard energy metric and this new quantity.

The theoretical part addressed in the project also raises questions given by the epistemological uncertainty to face: are we sure that the glasses we are wearing are the right ones to see the phenomenon we are investigating? To imagine the oil market as a natural phenomenon is a strong assumption and was somehow "simplified" by imagining that some more elementary market dynamics (the "swinging behavior" that shows the non-elasticity of the oil market) had similarities with the natural ecosystems.

The research has therefore focused on this, trying:

1. To find the dynamics of ecosystems that have similar behavior;
2. To establish analogies (the analogous swinging behavior in the spruce-budworm model) with the aim to strengthen our idea; and finally
3. To give a formalization of that (the differential equations converted into the Vensim implementation), supported by the literature on this topic.

In particular, the Vensim implementation opens further scenarios for the deepening and verification of these dynamics in more complex models.

Even if apparently simpler, the last task - the dissemination path and the scientific communication - is equally difficult to carry out.

Energy is invisible and, in our society, all people can use it in many forms and in a large amount per capita (in the Western world more than in other parts), without awareness[2]. Michael Greer, a non-academic researcher in the US, in his book[3] tells a

[2] See Figure 2, Chapter 2.

[3] Greer (2008).

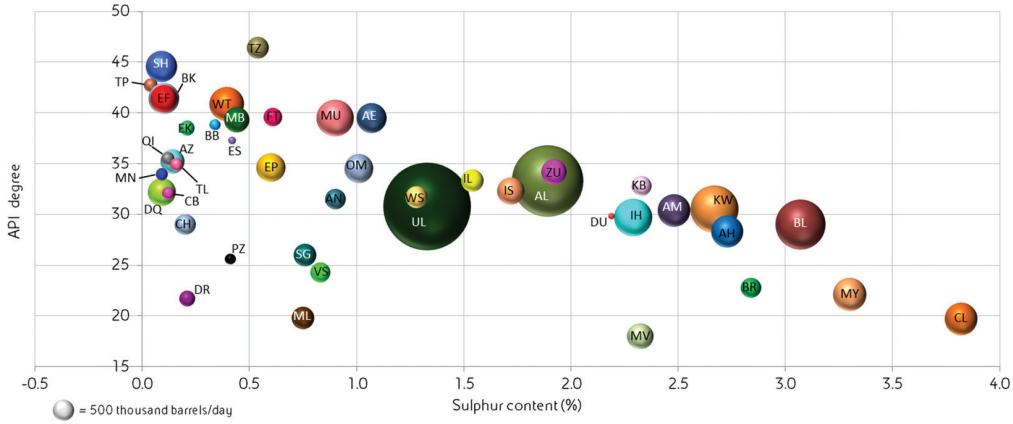
brief story on the path of the coffee, from the harvest to the table of the final user: «Consider a cup of coffee. The energy needed to run the coffee maker is only a tiny portion of the total petroleum-based energy and materials that go into the process. Unless the coffee is organically grown, chemical fertilizers and pesticides derived from oil are used to produce the beans; diesel-driven farm machinery harvests them; trucks, ships, and trains powered by one petroleum product or another move them around the world from producer to middleman to consumer, stopping at various fossil-fuel-heated or -cooled storage facilities and fossil-fuel-powered factories en route; consumers in the industrial world drive to brightly lit and comfortably climate-controlled supermarkets on asphalt roads to bring back plastic-lined containers of ground coffee to their homes. To drink coffee by the cup, we use oil by the barrel»[4].

The game on Hubbert's peak seems a good candidate to learn how resources can be depleted. The proposed improvements (transforming the game from real to virtual, making it becomes a smartphone app, expanding the dedicated website), mentioned in chapter 3 could make it a "viral" game and contribute to the efforts to create and improve an "energy awareness" that, in times of abundance, nobody seems to have.

[4] *Ibid*., p. 115.

# Appendix 1.
# The calculation of mean API degree

We have calculated the mean API degree with the support of O&G. World Oil and Gas review 2015[1]. This report, drawn up by ENI, on page 85 shows a graph "Quality and Production Volume of Main Crudes 2014" for the worldwide production of oil.




- UL - Urals (Russia)
- WT - West Texas Int. (U.S.A.)
- AL - Arab Light (Saudi Arabia)
- MB - Mixed Blend S. (Canada)
- AZ - Azeri Light (Azerbaijan)
- BB - Brent Blend (U.K.)
- KW - Kuwait (Kuwait)
- AM - Arab Medium (Saudi Arabia)
- BL - Basrah Light (Iraq)
- AH - Arab Heavy (Saudi Arabia)
- BR - Bow River (Canada)
- DQ - Daquing (China)
- CB - Cabinda (Angola)
- CH - Changqing (China)
- CL - Cold Lake (Canada)
- DR - Duri (Indonesia)
- EK - Ekofisk (U.K., Norway)
- EP - Espo (Russia)
- ES - Es Sider (Libya)
- FT - Forties (U.K.)
- IH - Iran Heavy (Iran)
- DU - Dubai (U.A.E.)
- IL - Iran Light (Iran)
- IS - Isthmus (Mexico)
- KB - Kirkuk Blend (Iraq)
- ML - Marlim (Brazil)
- MU - Murban (U.A.E.)
- AE - Arab Extra L. (Saudi Arabia)
- MV - Merey (Venezuela)
- MY - Maya (Mexico)
- OM - Oman (Oman)
- AN - Alaskan Nth. Sl. (U.S.A.)
- PZ - Pazflor (Angola)
- QI - Qua Iboe (Nigeria)
- MN - Minas (Indonesia)
- SG - Shengli (China)
- SH - Saharan B. (Algeria)
- TL - Troll (Norway)
- TP - Tapis (Malaysia)
- TZ - Tengiz (Kazakhstan)
- VS - Vasconia (Colombia)
- WS - West Texas Sour (U.S.A.)
- ZU - Upper Zakum (U.A.E.)
- BK - Bakken Blend (U.S.A.)
- EF - Eagle Ford (U.S.A.)

To perform the calculation we pick up two points in the midline of every circle. In this way we have calculated the diameter and also the area for each circle, normalized with the standard circle – the unit of 500 thousand of barrels/day. Therefore, in this

[1] Available at: http://www.eninorge.com/Documents/Rapporter/WOGR%202015%20unico.pdf

way we retrieve two information: the amount of the production and the API degree for that production. To establish the weight of each contribution we have calculated a simple weighted average, considering that for each circle the center represents the exact API degree:

| Site | 1st point | 2nd point | area | 1,000 barrels/d | API degree | Weighted mean |
|---|---|---|---|---|---|---|
| Default value in legenda | 11,72 | 9,60 | 3,54 | 500,00 | | 32,20 |
| UL - Urals (Russia) | 35,11 | 26,44 | 59,06 | 8.334,88 | 30,77 | |
| BB - Brent Blend (UK) | 39,39 | 38,32 | 0,90 | 126,89 | 38,85 | |
| BR - Bow River (Canada) | 23,74 | 21,75 | 3,14 | 442,88 | 22,74 | |
| DR - Duri (Indonesia) | 22,50 | 20,90 | 1,99 | 280,90 | 21,70 | |
| IH - Iran Heavy (Iran) | 31,58 | 27,85 | 10,96 | 1.546,94 | 29,72 | |
| ML - Marlim (Brazil) | 20,92 | 18,63 | 4,09 | 577,15 | 19,77 | |
| OM - Oman (Oman) | 35,98 | 33,02 | 6,89 | 972,37 | 34,50 | |
| SG - Shengli (China) | 27,13 | 24,87 | 4,01 | 566,08 | 26,00 | |
| VS - Vasconia (Colombia) | 25,30 | 23,26 | 3,26 | 459,88 | 24,28 | |
| WT - West Texas (USA) | 42,59 | 39,17 | 9,19 | 1.297,08 | 40,88 | |
| KW - Kuwait (Kuwait) | 32,88 | 28,19 | 17,31 | 2.442,01 | 30,53 | |
| DQ - Daquing (China) | 33,61 | 30,83 | 6,06 | 855,31 | 32,22 | |
| EK - Ekofisk (UK, Norway) | 39,28 | 37,74 | 1,87 | 263,19 | 38,51 | |
| DU - Dubai (UAE) | 30,15 | 29,50 | 0,33 | 46,97 | 29,83 | |
| MU - Murban (UAE) | 41,31 | 37,69 | 10,32 | 1.456,39 | 39,50 | |
| AN - Alaskan (USA) | 32,55 | 30,45 | 3,44 | 485,05 | 31,50 | |
| SH - Saharan (Algeria) | 46,16 | 43,05 | 7,57 | 1.068,52 | 44,60 | |
| WS - West Texas Sour (USA) | 32,81 | 30,59 | 3,90 | 550,16 | 31,70 | |
| AL - Arab Light (Saudi Arabia) | 36,81 | 29,77 | 39,01 | 5.505,45 | 33,29 | |
| AM - Arab Med. (Saudi Arabia) | 32,01 | 28,78 | 8,21 | 1.159,15 | 30,39 | |
| CB - Cabinda (Angola) | 32,75 | 31,43 | 1,35 | 190,78 | 32,09 | |
| EP - Espo (Russia) | 36,03 | 33,16 | 6,46 | 912,27 | 34,59 | |
| IL - Iranian Light (Iran) | 34,47 | 32,14 | 4,25 | 599,63 | 33,30 | |
| AE - Arab Extra (Saudi Arabia) | 41,00 | 38,01 | 7,02 | 990,84 | 39,51 | |
| PZ - Pazflor (Angola) | 26,13 | 25,04 | 0,93 | 131,68 | 25,59 | |
| TL - Troll (Norway) | 35,60 | 34,26 | 1,41 | 199,31 | 34,93 | |
| ZU - Upper Zakum (UAE) | 35,46 | 32,89 | 5,20 | 733,17 | 34,18 | |
| MB - Mixed Blend (Canada) | 40,63 | 38,06 | 5,19 | 732,60 | 39,34 | |
| BL - Basrah Light (Iraq) | 31,45 | 26,53 | 19,03 | 2.685,00 | 28,99 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| CH - Changqing (China) | 30,01 | 27,96 | 3,30 | 465,77 | 28,99 | |
| ES - Es Sider (Libia) | 37,66 | 36,87 | 0,49 | 68,47 | 37,26 | |
| IS - Isthmus (Mexico) | 33,66 | 30,92 | 5,93 | 836,94 | 32,29 | |
| MV - Merey (Venezuela) | 19,30 | 16,70 | 5,30 | 747,49 | 18,00 | |
| QI - Qua Iboe (Nigeria) | 36,15 | 34,86 | 1,30 | 183,01 | 35,51 | |
| TP - Tapis (Malaysia) | 43,43 | 41,99 | 1,62 | 227,91 | 42,71 | |
| BK - Bakken Blend (USA) | 42,98 | 39,82 | 7,81 | 1.101,82 | 41,40 | |
| AZ - Azeri Light (Azerbaijan) | 36,42 | 33,99 | 4,65 | 655,52 | 35,20 | |
| AH - Arab Heavy (Saudi Arabia) | 29,89 | 26,71 | 7,92 | 1.117,25 | 28,30 | |
| CL - Cold Lake (Canada) | 21,33 | 18,07 | 8,34 | 1.177,14 | 19,70 | |
| FT - Forties (UK) | 40,54 | 38,64 | 2,84 | 401,36 | 39,59 | |
| KB - Kirkuk Blend (Iraq) | 33,77 | 31,80 | 3,06 | 431,87 | 32,78 | |
| MY - Maya (Mexico) | 23,78 | 20,40 | 8,94 | 1.261,69 | 22,09 | |
| MN - Minas (Indonesia) | 34,61 | 33,31 | 1,32 | 186,15 | 33,96 | |
| TZ - Tengiz (Kazakistan) | 47,56 | 45,33 | 3,88 | 547,70 | 46,44 | |
| EF - Eagle Ford (USA) | 42,76 | 40,05 | 5,76 | 813,35 | 41,40 | |

# Appendix 2.
# The oil companies EROI

## A.2.1 Some methodological considerations

The SR analyzed are different each other and there are no standard followed by the oil companies, so it is necessary to stress some points:

- Some SR subdivided the company emissions into direct and indirect, complying with the guidelines issued by the GHG Protocol. For these companies we have calculated two kinds of EROI; in the first case only for direct emission caused by the company and, in the second one, for the sum of direct and indirect emissions. Often, we will see, there are small differences between these two values.
- Some SR report the emissions subdivided into $CO_2$ and other GHG ($NO_x$, $SO_x$, etc.), while better reports give us the value in $CO_2$ equivalent – the value normally used to calculate the EROI. In the first case, when we do not have this information, we had considered only the $CO_2$ emission, because it is however the most relevant contribution.
- The companies examined are usually "oil & gas". The production sometimes is reported separately for oil and gas, sometimes is put together, in tons (TOE) or barrels of oil equivalent (BOE). In all cases, we have converted the data into the best way to calculate the EROI estimate.
- The list of the companies examined have a descending order by revenues, from the highest to the lowest. In some cases, the companies are not involved only in extraction activities, but also make services for other companies (refinery, storing, transport and so forth). In these cases the EROI of the company examined falls down because values of extraction for oil and gas are low, but those of emissions are high - and in some cases even unrealistically because under the unity. This could mean indirectly that many oil companies - already with a not large EROI – in spite of the "Scope 3" indicated in the GHG Protocol, make outsourcing.

## A.2.2 Calculation method

1. It takes the initial production data which, fortunately, is almost always expressed in millions of barrels a day – and where it is not, it has been converted into this form [barrels/day], or, depending on how the emissions were expressed, it is left as a value in tons of daily (or yearly) oil production;
2. In the case of daily production, obviously, it has been multiplied by 365 to obtain the annual production (always either in barrels per year or in tons per year);
3. If the value is expressed in barrels, the value obtained in the previous step is multiplied by the conversion factor between cubic meters [mc] and barrels. The barrel of oil is 159 liters. One mc is 1,000 liters and therefore the factor 0.159 [mc/barrels];
4. This value is then multiplied by the average oil density that we have calculated previously (see Appendix 1), whence the value of 863.6 [kg/mc] came out;
5. The last operation to be carried out – if the emissions are in tons of $CO_2$ equivalent – is the multiplication related to the stoichiometric ratio between the molecular weight of a chain (the simplest) of hydrocarbons (methylene-$CH_2$: 14.03 g/mol) and carbon dioxide ($CO_2$: 44.01 g/mol), with a value of 3.14.

The dimensional analysis is:

[~~barrels~~/year] × [mc/~~barrels~~] = [mc/year] and then: [~~mc~~/year] × [kg/~~mc~~] = [kg/year] whence it is easier to infer the tons or million tons to be compared to the emissions.

As we can see in the following analysis, it is quite difficult to have a valid value of emissions for oil companies out of Western Countries, like the Arabian or the Middle East. Unfortunately, their "specific weight" is very high: for example, the first company of the list, Saudi Aramco, covers 10% of the oil market alone. In this appendix, we will discuss, case by case, the companies and the finding outcomes.

## A.2.3 The EROI calculation

### 01. Saudi Aramco – EROI: 52.29

This is the biggest oil company in the world, but its Annual Report 2015[1] offers only the oil production (p. 8) and no information about emissions. The company is

[1] Available at: http://www.saudiaramco.com/content/dam/Publications/annual-review/2015/English/AR-2015-SaudiAramco-English-full.pdf. All website on this section are checked in June 27 and 28, 2017.

property of the Saudi Monarchy but has recently announced[2], for a small portion (5%) of the entire capital, the launch of an IPO (Initial Public Offering) to enter in the Stock Exchange. The only useful information to know something about emissions is the intensity of energy requested for the production of one barrel of oil equivalent (1 BOE), expressed in thousands of BTU and equal to 108 for the 2015 (p. 66). The production is given separately for oil (91%) and NGL (9%). In this way, we have found an EROI at "mouth of the well" very high – probably because the operation involved is only the extraction.

| SAUDI ARAMCO | | |
|---|---|---|
| Oil | 10,200,000.00 | barrels/day[3] |
| | 365.00 | day/year |
| | 3,723,000,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 510,892,546,920.00 | kg/year |
| | 510.89 | mtons/year |
| | 3.14 | $CO^2/CH_2$ |
| | 1,602.59 | $mtCO_2eq$/year |
| | | |
| Ngl | 1,300,000.00 | barrels/day[4] |
| | 365.00 | day/year |
| | 474,825,000.00 | barrels/year |
| | 1,994,265,000.00 | btu conversion |
| | 356,118,750.00 | crude conversion |
| | 137.23 | barrels > kg |
| | 48,868,765,832.25 | kg/year |
| | 48.87 | mtons/year |
| | 2.74 | $CO_2/CH_4$ |
| | 134.08 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 1,736.68 | $mtCO_2eq$/year |
| | | >>> |

[2] https://www.forbes.com/sites/ellenrwald/2017/02/25/the-worlds-biggest-ipo-is-coming-what-you-should-know-about-aramco/#5749cfa4535f

[3] Saudi Aramco Annual Report 2015, p. 8.

[4] Saudi Aramco Annual Report 2015, p. 66.

| | | |
|---|---|---|
| Emissions | 108,000.00 | btu/barrel |
| | 453,365,100,000,000.00 | btu |
| | 77,072,067.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 10,576,599,754.41 | kg/year |
| | 10.58 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 33.21 | $mtCO_2eq$/year |
| | | |
| EROI | 52.29 | at “mouth of well” |

## 02. Sinopec – EROI: 1.67

The data are referred for the 2014 because there are no values, inside the SR, about emissions. Online[5] we have found an intensity value: «As part of its energy efficiency programme Sinopec aims to raise efficiency by 20 percent in 2014, or 14 million tonnes of coal equivalent, by cutting consumption at its refineries and power plants and improving its oil pumping systems». If 14 million are the 20%, then we presume that the 100% are 70 million. It was necessary to convert the value in TCE (tons of coal equivalent) in TOE (tons of oil equivalent) via BTU. The results are listed in the following table. The EROI found is very low but, as in the previous case, we are talking about a national company and probably, here, the EROI includes the entire cost, up to the final user.

| SINOPEC | | |
|---|---|---|
| Oil | 471,910,000.00 | boe/year[6] |
| | 137.23 | barrels>kg |
| | 64,760,209,300.00 | kg/year |
| | 64.76 | mtons/year |
| | | |
| Gas | 734.79 | bcf/year[7] |
| | 1,000.00 | cf > btu |
| | 734,790,000,000,000.00 | btu/year |
| | 124,914,300.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 17,141,989,389.00 | kg/year |
| | 17.14 | mtons/year |
| | | |
| Oil & Gas | 81.90 | mtons/year |
| | | |
| Emissions | 70,000,000.00 | tce |
| | 1,943,176,747,400,000.00 | btu |
| | 48,967,230.34 | toe > tons |
| | 48.97 | mtons/year |
| | | |
| EROI | 1.67 | |

[5] http://af.reuters.com/article/energyOilNews/idAFL4N0P807H20140627

[6] Sinopec Annual Report and Accounts 2015, p. 12, available at: http://www.sinopec.com/listco/en/Resource/Pdf/2016032918C.pdf

[7] www.statista.com/statistics/227293/sinopecs-natural-gas-production/ For the calculation of the EROI of Chinese oil companies, we also consulted Zhao-Yang Kong et al. (2016).

## 03. China National Petroleum Company (CNPC) – EROI: not available

The production data is available on the Annual Report 2015 (p. 7)[8] and is separated for oil and gas. However, nothing is possible to know about emissions. Therefore, the value of EROI is not available.

| CHINA NATIONAL PETROLEUM | | |
|---|---|---|
| Oil | 111.43 | mtoe/year |
| | 3.14 | $CO_2/CH_2$ |
| | 349.54 | $mtCO_2eq$/year |
| | | |
| Gas | 95.48 | bcm/year |
| | 3.371.844.691.600.000.00 | bcm > btu |
| | 573.213.597.57 | btu > boe |
| | 137.23 | barrels > kg |
| | 78.662.101.994.81 | kg/year |
| | 78.66 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 247.00 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 596.54 | $mtCO_2eq$/year |
| | | |
| Emissions | NOT AVAILABLE | |
| | | |
| EROI | NOT AVAILABLE | |

[8] http://www.cnpc.com.cn/en/xhtml/pdf/2015_Annual_Report_online/0-2015_Annual_Report.pdf

## 04. PetroChina – EROI: 3.63

The aggregate production data for oil and gas can be found on page 3 of the report[9], while the emissions – issued in TCE – are under the heading "total energy consumption". The value of EROI thus determined is therefore very low.

| PETROCHINA | | |
|---|---|---|
| Oil | 961,630,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 131,964,484,900.00 | kg/year |
| | 131.96 | mtons/year |
| | | |
| Gas | 3,131.00 | bcf/year[10] |
| | 3,131,000,000,000,000.00 | bcf > btu |
| | 532,270,000.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 73,043,412,100.00 | kg/year |
| | 73.04 | mtons/year |
| | | |
| Oil & gas | 205.00 | mtons/year |
| | | |
| Emissions | 80.77 | tce |
| | 56.51 | mtons/year |
| | | |
| EROI | 3.63 | |

[9] http://www.petrochina.com.cn/petrochina/xhtml/images/shyhj/2015kcxfzbgen02.pdf
[10] https://www.statista.com/statistics/232509/natural-gas-production-volume-of-petrochina/

## 05. Exxon Mobil – EROI: 7.59

The production data is available on the Annual Report (p. 5)[11]. The output data is on the Corporate Citizenship Report at p. 35.

| EXXON | | |
|---|---|---|
| Oil | 4,097,000.00 | barrels/day |
| | 365.00 | day/year |
| | 1,495,405,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 205,214,428,150.00 | kg/year |
| | 205.21 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 644.37 | $mtCO_2eq$/year |
| | | |
| Gas | 10,515.00 | mcf/day |
| | 3,837,975.00 | mcf/year |
| | 1,000.00 | cf > btu |
| | 3,837,975,000,000,000.00 | btu/year |
| | 652,455,750.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 89,536,502,572.50 | kg/year |
| | 89.54 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 281.14 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 925.51 | $mtCO_2eq$/year |
| | | |
| Emissions | 122.00 | $mtCO_2eq$/year |
| | | |
| EROI | 7.59 | |

[11] http://cdn.exxonmobil.com/~/media/global/files/corporate-citizenship-report/2015_corporate_citizenship_report_full_approved-pdf.pdf

**06. Shell – EROI: 7.75*, 6.88****

The SR[12] reports 3 million barrels of oil equivalent per day (p.5), direct emissions of 72 million tons annually and indirectly of 9 million tons (p.52). So the values are listed in the following table.

| SHELL | | |
|---|---|---|
| Oil | 3,000,000.00 | barrels/day |
| | 365.00 | day/year |
| | 1,095,000,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 150,262,513,800.00 | kg/year |
| | 150.26 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 471.35 | $mtCO_2eq$/year |
| | | |
| Gas | 22.60 | million tons gas/year[13] |
| | 201,140,000.00 | mtons > boe |
| | 137.23 | barrels > kg |
| | 27,602,442,200.00 | kg/year |
| | 27.60 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 86.67 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 558.02 | $mtCO_2eq$/year |
| | | |
| Emissions * | 72.00 | $mtCO_2eq$/year |
| Emissions ** | 81.00 | $mtCO_2eq$/year |
| | | |
| EROI* | 7.75 | |
| EROI** | 6.88 | |

* Direct emissions.

** Direct + indirect emissions.

[12] https://reports.shell.com/sustainability-report/2015/servicepages/downloads/files/entire_shell_sr15.pdf

[13] http://reports.shell.com/annual-report/2015/strategic-report/upstream/production.php

## 07. Kuwait Petroleum – EROI: 19.86

There is an anomaly because the last SR[14] (to know the emissions) is referred to 2012, while the production is online[15]: «With 120 years of known reserves and crude oil production levels of 2.9 million barrels per day, it is ranked the seventh largest oil producer in the world». The data about GHG emissions are shown separately (SR, page 25). If we sum all values the result is 7,983 tons per year, but anyway the EROI is rather high.

| KUWAIT PETROLEUM | | |
|---|---|---|
| Oil | 2,900,000.00 | barrels/day |
| | 365.00 | day/year |
| | 1,058,500,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 145,253,763,340.00 | kg/year |
| | 145.25 | mtons/year |
| | | |
| Gas | 16.06 | bcm/year[16] |
| | 567,153,600,200,000.00 | bcm > btu |
| | 96,416,112.03 | btu > boe |
| | 137.23 | barrels > kg |
| | 13,231,183,054.43 | kg/year |
| | 13.23 | mtons/year |
| | | |
| Oil & Gas | 158.48 | mtons/year |
| | | |
| Emissions | 7.98 | mtons/year |
| | | |
| EROI | 19.86 | |

[14] https://www.kpc.com.kw/Sustainability%20Reports/KPI%20CSR%20Report%202012.pdf
[15] https://www.q8oils.com/en-us/en/mainnavigation/aboutus.aspx
[16] https://ycharts.com/indicators/kuwait_natural_gas_production

## 08. British Petroleum (BP) – EROI: 11.23*, 9.74**

We have two results calculated for direct and indirect emissions. All data are available on the SR[17], page 8.

| BRITISH PETROLEUM | | |
|---|---|---|
| Oil | 729,649,388.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 100,129,785,515.24 | kg/year |
| | 100.13 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 314.41 | $mtCO_2eq$/year |
| | | |
| Gas | 7,146.00 | mcf/day[18] |
| | 2,608,290.00 | mcf/year |
| | 2,608,290,000,000,000.00 | mcf > btu |
| | 443,409,300.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 60,849,058,239.00 | kg/year |
| | 60.85 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 191.07 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 505.48 | $mtCO_2eq$/year |
| | | |
| Emissions* | 45.00 | $mtCO_2eq$/year |
| Emissions** | 51.90 | $mtCO_2eq$/year |
| | | |
| EROI* | 11.23 | |
| EROI** | 9.74 | |

* Direct emissions.

** Direct + indirect emissions.

[17] https://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/bp-sustainability-report-2015.pdf

[18] http://statista.com/statistics/305232/natural-gas-reserves-and-production-of-bp/

## 09. Total SA – EROI: 10.81

The website is a little bit disorganized, but all data about 2015 are in the "registration document"[19]: the production on page 1 and the emissions on page 145.

| TOTAL SA | | |
|---|---|---|
| Oil | 2,347,000.00 | boe/day |
| | 365.00 | day/year |
| | 856,655,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 117,555,373,296.20 | kg/year |
| | 117.56 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 368.75 | $mtCO_2eq$/year |
| | | |
| Gas | 66.40 | bcm/year (2016)[20] |
| | 2,344,894,088,000,000.00 | bcm > btu |
| | 398,631,994.96 | btu > boe |
| | 137.23 | barrels > kg |
| | 54,704,268,668.36 | kg/year |
| | 54.70 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 171.77 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 540.52 | $mtCO_2eq$/year |
| | | |
| Emissions | 50.00 | $mtCO_2eq$/year |
| | | |
| EROI | 10.81 | |

[19] http://www.total.com/sites/default/files/atoms/files/registration_document_2015.pdf
[20] https://www.total.com/en/news/natural-gas-integral-part-totals-strategy

**10: Lukoil – EROI: 5.83**

There are no data for the same year. We have picked up the data about production from the Annual Report 2015[21] (page 227) and, for the emissions, the only sure data come from the website of the company[22], even if they cover five years (2008-2012). We simply calculated an arithmetic mean of the available data over the five years.

| LUKOIL | | |
|---|---|---|
| Oil | 736.000.000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 101,001,280,000.00 | kg/year |
| | 101.00 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 317.14 | $mtCO_2eq$/year |
| | | |
| Gas | 154,000,000.00 | boe/year[23] |
| | 137.23 | barrels > kg |
| | 21,133,420,000.00 | kg/year |
| | 21.13 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 66.36 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 383.5 | $mtCO_2eq$/year |
| | | |
| Emissions | 65.74 | $mtCO_2eq$/year |
| | | |
| EROI | 5.83 | |

[21] http://www.lukoil.ru/FileSystem/PressCenter/27396.pdf?dl=1

[22] http://www.lukoil.com/Responsibility/SafetyAndEnvironment/Ecology/GasEmissionRegulation

[23] http://www.lukoil.com/FileSystem/9/227307.xlsx?dl=1 downloadable from: http://www.lukoil.com/Business/Upstream/DevelopmentAndProduction

## 11: Ente Nazionale Idrocarburi (ENI) – EROI: 10.43

ENI produce 1.76 million of BOE per day (p. 4 of "ENI Fact Book")[24] and sustain to emit 38.5 million of tons of GHG (direct emissions, p. 4 of SR)[25].

| ENI | | |
|---|---|---|
| Oil | 1,760,000.00 | barrels/day |
| | 365.00 | day/year |
| | 642,400,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 88,154,008,096.00 | kg/year |
| | 88.15 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 276.53 | $mtCO_2eq$/year |
| | | |
| Gas | 4,681.00 | mcf/day |
| | 1,708,565.00 | mcf/year |
| | 1,708,565,000,000,000.00 | bcm > btu |
| | 290,456,050.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 39,859,283,741.50 | kg/year |
| | 39.86 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 125.16 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 401.69 | $mtCO_2eq$/year |
| | | |
| Emissions | 38.50 | $mtCO_2eq$/year |
| | | |
| EROI | 10.43 | |

[24] https://www.eni.com/docs/en_IT/enicom/company/fact-book-2015-eng.pdf
[25] https://www.eni.com/docs/en_IT/enicom/sustainability/eni_for_2015_report_eng_.pdf

**12: Valero – EROI: not available**

Valero is basically a tertiary company that is likely to refine oil and other materials for other companies, at claimed least according to what is declared on its SR: «Valero Energy Corporation, through its subsidiaries, is a global manufacturer, distributor and marketer of transport fuels, petrochemical Products and power. Valero's subsidiaries employ approximately 10,000 people, and assets include 15 petroleum refineries with a combined throughput capacity of approximately 3 million barrels per day, 11 ethanol plants with a combined production capacity of 1.3 billion gallons per year» (p. 2 of the SR)[26]. Even if it is rather difficult to estimate the amount of treated materials, the problem remains that data about emissions are lacking.

**13: Petrobras – EROI: 5.65**

Both production and emissions are available on the SR (p. 2)[27].

| PETROBRAS | | |
|---|---|---|
| Oil | 2,230,000.00 | barrels/day[28] |
| | 813,950,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 111,698,358,500.00 | kg/year |
| | 111.70 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 350.73 | $mtCO_2eq$/year |
| | | |
| Gas | 560,000,00 | barrels/day |
| | 204,400,000,00 | barrels/year |
| | 137,23 | barrels > kg |
| | 28,049,812,000,00 | kg/year |
| | 28,05 | mtons/year |
| | 3,14 | $CO_2/CH_2$ |
| | 88,08 | $mtCO_2eq$/year |
| | | >>> |

[26] https://www.energievalero.ca/en-ca/PublishingImages/Company/ResourceCenter/2015%20Social%20Responsability%20Report.pdf

[27] http://www.petrobras.com.br/lumis/portal/file/fileDownload.jsp?fileId=8A8B2D16572EBA5C0158D44479594FC5

[28] http://www.investidorpetrobras.com.br/en/press-releases/oil-and-natural-gas-production-2015

| | | |
|---|---|---|
| Oil & Gas | 438.81 | $mtCO_2eq/year$ |
| | | |
| Emissions | 77.70 | $mtCO_2eq/year$ |
| | | |
| EROI | 5.65 | |

**14: Chevron – EROI: 9.70**

The production is available on the Annual Report[29] (p. 5), while the value of emissions on the SR[30] (p. 24).

| CHEVRON | | |
|---|---|---|
| Oil | 2,622,000.00 | boe/day |
| | 365.00 | day/year |
| | 957,030,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 131,333,226,900.00 | kg/year |
| | 131.33 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 411.97 | $mtCO_2eq/year$ |
| | | |
| Gas | 5,269.00 | mcf/day |
| | 1,923,185.00 | mcf/year |
| | 1,923,185,000,000,000.00 | bcm > btu |
| | 326,941,450.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 44,866,175,183.50 | kg/year |
| | 44.87 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 140.88 | $mtCO_2eq/year$ |
| | | |
| Oil & Gas | 552.85 | $mtCO_2eq/year$ |
| | | |
| Emissions | 57,00 | $mtCO_2eq/year$ |
| | | |
| EROI | 9.70 | |

[29] https://www.chevron.com/-/media/chevron/annual-report/2015/2015-Annual-Report.pdf
[30] https://www.chevron.com/-/media/chevron/shared/documents/2015-corporate-responsibility-report.pdf

**15: PDVSA (Venezuela) – EROI: not available**

The production is retrieved from a communication agency (Reuters)[31] but nothing is possible to know about emissions. The company website in some part is "updated" at 2007 and, nowadays, the country has more serious problems to face.

| PDVSA | | |
|---|---|---|
| Oil | 2,863,000.00 | barrels/day |
| | 1,044,995,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 143,404,663,850.00 | kg/year |
| | 143.40 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 450.29 | $mtCO_2eq$/year |
| | | |
| Gas | 5,296.00 | mcf/day[32] |
| | 1,933,040.00 | mcf/year |
| | 1,933,040,000,000,000.00 | mcf > btu |
| | 328,616,800.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 45,096,083,464.00 | kg/year |
| | 45.10 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 141.60 | $mtCO_2eq$/year |
| | | |
| | | |
| Oil & Gas | 591.89 | $mtCO_2eq$/year |
| | | |
| Emissions | NOT AVAILABLE | |
| | | |
| EROI | NOT AVAILABLE | |

[31] http://uk.reuters.com/article/venezuela-pdvsa-production-idUKL2N0XE1CE20150420

[32] http://www.pdvsa.com/index.php?option=com_content&view=article&id=6545&Itemid=900&lang=en

## 16: Pemex – EROI: 7.88

The SR is updated to 2014[33], therefore we carried out the calculation for this year. Data about emissions can be found on the SR (p. 87), while the production is available in the Monthly Petroleum Statistics[34].

| PEMEX | | |
|---|---|---|
| Oil | 773.825.550,00 | barrels/year |
| | 137.23 | barrels > kg |
| | 106,192,080,226.50 | kg/year |
| | 106.19 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 333.44 | $mtCO_2eq$/year |
| | | |
| | | |
| Gas | 3,929.00 | mcf/day[35] |
| | 1,434,085.00 | mcf/year |
| | 1,434,085,000,000,000.00 | bcm > btu |
| | 243,794,450.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 33,455,912,373.50 | kg/year |
| | 33.46 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 105.05 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 438.49 | $mtCO_2eq$/year |
| | | |
| Emissions | 55.62 | $mtCO_2eq$/year |
| | | |
| EROI | 7.88 | |

[33] http://www.pemex.com/responsabilidad/sustentable/informes/Documents/informeresponsabildiad_2014.pdf

[34] http://www.pemex.com/en/investors/publications/Indicadores%20Petroleros%20Archivos/eprohidro_ing.pdf

[35] http://www.pemex.com/en/investors/publications/Indicadores%20Petroleros%20Archivos/eprodcrudo_ing.pdf

## 17: National Iranian Oil Company (NIOC) – EROI: 1.30

The production data can be found on the company's website at the following address: http://www.nioc.ir/portal/Home/ShowPage.aspx?Object=NEWS&ID=84aedbc4-c7e4-4f49-9b3b-ae95787258d7&LayoutID=ba9beea1-5bfb-4b05-8edf-39-b84db5a4ec&CategoryID=a034ee3f-1acf-4bad-a4af-1bbbf5c1e716.

Site copyright is 2009, while the "headline" (a sort of recent news roll) dates back to 2012. The webpage about reports exists, but it is a kind of empty box[36]. The general feeling is that the site was abandoned, especially because the page where the reports should be found has no content. The only information available on the web is an old estimate of the $CO_2$ consumption of the *whole* nation in 2008[37].

| NATIONAL IRANIAN OIL COMPANY | | |
|---|---|---|
| Oil | 489,349,513.14 | barrels/year |
| | 137.23 | barrels > kg |
| | 67,153,433,688.20 | kg/year |
| | 67.15 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 210.86 | $mtCO_2eq$/year |
| | | |
| Gas | 189.04 | bcm/year[38] |
| | 6,675,885,216,800,000.00 | bcm > btu |
| | 1,134,900,486.86 | btu > boe |
| | 137.23 | barrels > kg |
| | 155,742,393,811.25 | kg/year |
| | 155.74 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 489.03 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 699.89 | $mtCO_2eq$/year |
| | | >>> |

[36] http://www.nioc.ir/portal/home/default.aspx?categoryid=1749ab39-6590-49b0-a616-930afcbc8233&tabno=4

[37] http://cdiac.ornl.gov/ftp/trends/emissions/ira.dat and this – even if we assume NIOC as the only Iranian oil producer – makes EROI very low, and probably biased. However, in the table the calculation is illustrated.

[38] http://en.nioc.ir/Portal/File/ShowFile.aspx?ID=a05977b6-5baf-4f8a-acb7-4f6da39133e6

| | | |
|---|---|---|
| Emissions | 146,824.00 | thousand metric tons of carbon |
| | 3.67 | conversion factor |
| | 538,403.61 | thousand $tCO_2eq$/year |
| | 538.40 | $mtCO_2eq$/year |
| | | |
| EROI | 1.30 | |

**18: Gazprom – EROI: 11.65**

The production for 2015 is on the website[39]: 418.5 billion cubic meters of gas; 15.3 million tons of gas condensate and 36 million tons of oil. The data about emissions are on the SR[40], p. 23.

| GAZPROM | | |
|---|---|---|
| Oil | 36.00 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 112.93 | $mtCO_2eq$/year |
| | | |
| Gas | 418.50 | bcm/year |
| | 14,779,189,395,000,000.00 | bcm > btu |
| | 2,512,462,197.15 | btu > boe |
| | 137.23 | barrels > kg |
| | 344,785,187,314.89 | kg/year |
| | 344.79 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 1,082.63 | $mtCO_2eq$/year |
| | | |
| Gas condensate | 15.30 | mtons/year |
| | 136,170,000.00 | mtons > boe |
| | 137.23 | barrels > kg |
| | 18,686,609,100.00 | kg/year |
| | 18.69 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 58.68 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 1,195.56 | $mtCO_2eq$/year |
| | | >>> |

[39] http://www.gazprom.com/about/production/extraction/
[40] http://www.gazprom.com/f/posts/12/001311/gazprom-ecology-report-2015-en.pdf

| | | |
|---|---|---|
| Emissions | 102.60 | $mtCO_2eq/year$ |
| | | |
| EROI | 11.65 | |

**19: Petronas – EROI: 7.93**

The production is on the company website[41], while the emissions are on the SR[42], p. 60.

| PETRONAS | | |
|---|---|---|
| Oil | 641,301,500.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 88,005,804,845.00 | kg/year |
| | 88.00 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 276.33 | $mtCO_2eq/year$ |
| | | |
| Gas | 28.49 | mtons/year[43] |
| | 253,561,000.00 | mtons > boe |
| | 137.23 | barrels > kg |
| | 34,796,176,030.00 | kg/year |
| | 34.80 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 109.26 | $mtCO_2eq/year$ |
| | | |
| Oil & Gas | 385.59 | $mtCO_2eq/year$ |
| | | |
| Emissions | 48.63 | $mtCO_2eq/year$ |
| | | |
| EROI | 7.93 | |

[41] http://www.petronas.com.my/media-relations/media-releases/Pages/article/Q1-FY2016.aspx

[42] http://www.petronas.com.my/sustainability/Documents/sustainability-report/SustainabilityReport2015.pdf

[43] http://www.petronas.com.my/media-relations/media-releases/Pages/article/HIGHER-2016-PROFIT-FOR-PETRONAS.aspx

## 20: China National Offshore Oil Company (CNOOC) – EROI: 11.20

On page 14 of the SR[44] we find all the data, both output and – indirectly – emission. While production data are clearly expressed, emission issues need to be treated, as they are expressed not as energy but as capital intensity. The company's earnings for 2015 are 468,900,000,000 RMB (yuan) and the energy intensity is calculated as a fraction of this capital, ie: 0.2731 TCE / 10,000 RMB. Multiplying the two values we determine how many tons of equivalent carbon (TCE) were produced in a year. This value has to be transformed into million tons of equivalent oil, so that it can be properly correlated with the production data for the calculation of EROI.

| CHINA NATIONAL OFFSHORE OIL COMPANY | | |
|---|---|---|
| Oil | 79,700,000.00 | tons/year |
| | 79.70 | mtons/year |
| | | |
| Gas | 25,100.00 | mcm/year |
| | 886,398,217,000,000.00 | mcm > btu |
| | 150,687,696.89 | btu > boe |
| | 137.23 | barrels > kg |
| | 20,678,872,644.21 | kg/year |
| | 20.68 | mtons/year |
| | | |
| Oil & Gas | 100.38 | mtons/year |
| | | |
| Emissions | 468,900,000,000.00 | RMB |
| | 0.27 | tce/10,000 RMB |
| | 12,805,659.00 | tce/year |
| | 8,958,690.53 | toe/year |
| | 8.96 | mtons/year |
| | | |
| EROI | 11.20 | |

[44] http://www.cnooc.com.cn/attach/0/1605101600110775579.pdf

## 21: Marathon Petroleum – EROI: 11.38*, 8.41**

Both data about emissions and production are concentrated on pages 63-64 of the citizenship report[45]. In this case, we have both direct and indirect emissions so we have made two different calculation for the EROI.

| MARATHON PETROLEUM | | |
|---|---|---|
| Oil | 1,142,000.00 | barrels/day |
| | 365.00 | day/year |
| | 416,830,000.00 | barrels/year |
| | 137.23 | barrels > kg |
| | 57,199,930,253.20 | kg/year |
| | 57.20 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 179.43 | $mtCO_2eq$/year |
| | | |
| Gas | 285,430.00 | mcf/year[46] |
| | 285,430,000,000,000.00 | mcf > btu |
| | 48,523,100.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 6,658,825,013.00 | kg/year |
| | 6.66 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 20.91 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 200.34 | $mtCO_2eq$/year |
| | | |
| Emissions* | 17.60 | $mtCO_2eq$/year |
| Emissions** | 23.80 | $mtCO_2eq$/year |
| | | |
| EROI* | 11.38 | |
| EROI** | 8.41 | |

* Direct emissions.

** Direct + indirect emissions.

[45] http://www.marathonpetroleum.com/content/documents/Citizenship/2016/2016_Citizenship_Report.pdf

[46] Annual report 2017, available at: http://www.annualreports.com/Company/marathon-oil-corporation

## 22. PTT (Thailand) – EROI: 24.95*, 24.89**

The Annual Report[47] is more complete than the SR. The production is available on page 32, while emissions – direct and indirect – are on page 34.

| PTT | | |
|---|---|---|
| Oil | 136,000,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 18,662,741,440.00 | kg/year |
| | 18.66 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 58.54 | $mtCO_2eq$/year |
| | | |
| Gas | 618,00 | bcf/year |
| | 618,000,000,000,000,00 | mcf > btu |
| | 105,060,000,00 | btu > boe |
| | 137,23 | barrels > kg |
| | 14,417,383,800,00 | kg/year |
| | 14,42 | mtons/year |
| | 3,14 | $CO_2/CH_2$ |
| | 45,27 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 103.81 | $mtCO_2eq$/year |
| | | |
| Emissions* | 4.16 | $mtCO_2eq$/year |
| Emissions** | 4.17 | $mtCO_2eq$/year |
| | | |
| EROI* | 24.95 | |
| EROI** | 24.89 | |

* Direct emissions.
** Direct + indirect emissions.
[47] https://www.pttep.com/en/OurBusiness/Publications/2015Annualreport.aspx

**23: Rosneft – EROI: 21.14*, 13.12****

All data are available on the SR[48]: the production on page 6 and the emissions on page 74.

| ROSNEFT | | |
|---|---|---|
| Oil | 1,883,000,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 258,404,090,000.00 | kg/year |
| | 258.40 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 810.57 | $mtCO_2eq$/year |
| | | |
| Gas | 62.50 | billion cubic meters |
| | 2,207,166,875,000,000.00 | bcf > btu |
| | 375,218,368.75 | btu > boe |
| | 137.23 | barrels > kg |
| | 51,491,216,743.56 | kg/year |
| | 51.49 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 161.68 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 972.25 | $mtCO_2eq$/year |
| | | |
| Emissions* | 46.00 | $mtCO_2eq$/year |
| Emissions** | 74.10 | $mtCO_2eq$/year |
| | | |
| EROI* | 21.14 | |
| EROI** | 13.12 | |

* Direct emissions.

** Direct + indirect emissions.

[48] https://www.rosneft.com/upload/site2/document_file/RN_SR2016_eng_20160929.pdf

## 24: JX Holdings – EROI: 2.68

The production is in the Annual Report (p. 2)[49], limited to 2014 and analytically extrapolated via software (115,000 boe/day). The emissions are available on the SR (p. 82)[50] and splitted by scope. We are interested in scope 3 (upstream) and we sum those values (1,337 + 233 + 1) × 104 = 15,710,000 $tCO_2eq$ = 15.71 $mtCO_2eq$.

This value seems to concern more than one year because, on the same page, we can read «Starting in fiscal 2013, we began estimating and disclosing the target scope of JX Nippon Oil & Energy's petroleum division supply chain». Therefore, does the count in the table begin in 2013 and end in 2014? If it is true, the value found should be divided by two, at least. Also in this case the EROI is very low.

| JX HOLDINGS | | |
|---|---|---|
| Oil | 115,000.00 | boe/day |
| | 365.00 | day/year |
| | 41,975,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 5,760,229,250.00 | kg/year |
| | 5.76 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 18.07 | $mtCO_2eq$/year |
| | | |
| Gas | 790,000.00 | tons/year[51] |
| | 7,031,000.00 | mtons > boe |
| | 137.23 | barrels > kg |
| | 964,864,130.00 | kg/year |
| | 0.96 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 3.03 | $mtCO_2eq$/year |
| | | |
| Oil & gas | 21.10 | $mtCO_2eq$/year |
| | | |
| emissions | 7.86 | $mtCO_2eq$/year |
| | | |
| EROI | 2.68 | |

[49] http://www.hd.jxtg-group.co.jp/english/ir/library/annual/2014/pdf/jx_en_ar_fy2014.pdf

[50] https://www.unglobalcompact.org/system/attachments/cop_2015/222541/original/csr_report-2015-en.PDF?1451012531

[51] Annual Report 2016, available at https://www.hd.jxtg-group.co.jp/english/ir/library/annual/2015/.../jx_en_ar_fy2015.pdf

### 25: ENGIE – EROI: not available

This is the only company that has both production and emissions values, but not useful to calculate the EROI. Engie is involved in 70 countries and its business goes from the energy services supply to many and different energy resources (nuclear, NGL, oil, coal) management and production.

### 26: StatOil – EROI: 28.37

Statoil has the data in the SR[52]: production on page 2 and emissions on page 17.

| STATOIL | | |
|---|---|---|
| Oil | 787,935,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 108,128,320,050.00 | kg/year |
| | 108.12 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 339.52 | $mtCO_2eq$/year |
| | | |
| | | |
| Gas | 285,065,000.00 | boe/year[53] |
| | 137.23 | barrels > kg |
| | 39,119,469,950.00 | kg/year |
| | 39.12 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 122.84 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 462.36 | $mtCO_2eq$/year |
| | | |
| Emissions | 16.30 | $mtCO_2eq$/year |
| | | |
| EROI | 28.37 | |

[52] https://www.statoil.com/content/dam/statoil/documents/sustainability-reports/statoil-sustainability-report-2015.pdf
[53] Annual Report 2015.

## 27: Indian Oil Company – EROI: 3.70

This company, like others, is involved in many business fields (refinery, sales of energy and so on): we have choose only the refinery activities (p. 10 of SR[54]). For those activities the emissions are indicated on page 74.

| INDIAN OIL COMPANY | | |
|---|---|---|
| Oil | 56.69 | mtons/year |
| | | |
| LNG | 1,920,000.00 | tons/year |
| | 17,088,000.00 | mtons > boe |
| | 137.23 | barrels > kg |
| | 2,344,986,240.00 | kg/year |
| | 2.34 | mtons/year |
| | | |
| Oil & LNG | 59.03 | mtons/year |
| | | |
| Emissions | 15.96 | mtons/year |
| | | |
| EROI | 3.70 | |

[54] https://www.iocl.com/download/Sustainability_Report_2015-16.pdf

**28: Sonatrach – EROI: 22.56**

In the Annual Report[55] we will find the production for 2014 (p. 11) and the only data retrieved about emissions are in the sentence on page 37: «Les Emissions atmosphériques: le volume de gaz torchés en 2014 au niveau des unités opérationnelles relevant de l'opérationel a atteint 4744 Millions $m^3$». If we can consider correct this value as "emissions", the calculation is as follows:

| SONATRACH | | |
|---|---|---|
| Oil | 50.70 | mtons/year |
| | | |
| Gas | 39.50 | bcm/year[56] |
| | 1,394,929,465,000,000.00 | bcm > btu |
| | 237,138,009.05 | btu > boe |
| | 137.23 | barrels > kg |
| | 32,542,448,981.93 | kg/year |
| | 32.54 | mtons/year |
| | | |
| Oil & Gas | 83.24 | mtons/year |
| | | |
| Emissions | 4,474.00 | mcm/year |
| | 157,997,833,580,000.00 | mcm > btu |
| | 26,859,631.71 | btu > boe |
| | 137.23 | barrels > kg |
| | 3,685,947,259.37 | kg/year |
| | 3.69 | mtons/year |
| | | |
| EROI | 22.56 | |

[55] http://www.sonatrach.dz/docs/rapport_annuel_2014.pdf

[56] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2016/05/Algerian-Gas-Troubling-Trends-Troubled-Policies-NG- 108.pdf

## 29: Reliance Industries – EROI: 28.58

This company is cited also in one of the last books by Alan Weisman, about overpopulation (*Countdown*): «Even the richest man in town, Mukesh Ambani, chairman of the energy and materials conglomerate Reliance Industries, who's built a twenty-seven-floor, four-hundred-thousand-square-foot home for his family, doesn't run off the neighbors living in the cracks between the surrounding buildings, because his mansion needs a staff of six hundred». Trying to extrapolate two simple data like extraction/production of oil and emission, sometimes we need to face the complexity of those companies involved in many kinds of business and, above all, in parts of world where many stuffs are complex. So in this case our analysis could be affected by some bias and the EROI in itself reveals its limit. However, values are in the SR[57]: page 49 for production and 63 for GHG emissions. The EROI, in this case, is rather high.

| RELIANCE INDUSTRIES | | |
|---|---|---|
| Oil | 0.16 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 0.50 | $mtCO_2eq$/year |
| | | |
| Gas | 2,678.00 | mcm/year |
| | 94,572,686,260,000.00 | mcm > btu |
| | 16,077,356.66 | btu > boe |
| | 137.23 | barrels > kg |
| | 2,206,295,655.03 | kg/year |
| | 2.21 | mtons/year |
| | 3.14 | $CO_2/CH_2$ |
| | 6.93 | $mtCO_2eq$/year |
| | | |
| Oil & Gas | 7.43 | $mtCO_2eq$/year |
| | | |
| Emissions | 0.26 | $mtCO_2eq$/year |
| | | |
| EROI | 28.58 | |

[57] http://www.ril.com/DownloadFiles/SustainiabilityReports/RIL's%20G4%20Sustainability%20Report%202014-15.pdf

**30: Pertamina – EROI: 8.04**

Both production (p. 34) and emissions (p. 134) are available on the SR[58].

| PERTAMINA | | |
|---|---|---|
| Oil | 101,600,000.00 | boe/year |
| | 137.23 | barrels > kg |
| | 13,942,165,664.00 | kg/year |
| | 13.94 | mtons/year |
| | | |
| Gas | 694.33 | bcf/year |
| | 694,330,000,000,000.00 | bcf > btu |
| | 118,036,100.00 | btu > boe |
| | 137.23 | barrels > kg |
| | 16,198,094,003.00 | kg/year |
| | 16.20 | mtons/year |
| | | |
| Oil & Gas | 30.14 | mtons/year |
| | | |
| Emissions | 3.75 | mtons/year |
| | | |
| EROI | 8.04 | |

[58] http://www.pertamina.com/media/d2d30686-149d-4121-a63e-0dd6a776d1ee/SR_Pertamina_2015.pdf

# Appendix 3.
# Dissemination and outreach[1]

## A.3.1 Articles

- *Il pianeta Terra e il punto di non ritorno*, «Scienze & Ricerche», 14, 1 October 2015, pp. 5-8.
- *Cos'è cambiato nel cambiamento climatico?*, «Scienze & Ricerche», 25, 15 March 2016, pp. 5-13.
- *Zoo e dinamiche della catastrofe: dalle balene ai cigni*, «Scienze & Ricerche» (peer reviewed), 26, 1 April 2016, pp. 72-80.
- *La questione energetica è anche una questione etica?*, «Scienze & Ricerche», 34, 1 August 2016, pp. 5-11.
- *Il cambiamento climatico comporta un cambiamento sociale?*, «Nuova Secondaria», year XXXIV, 1, September 2016, pp. 99-101.
- *La "marmitta di Gaia": quante emissioni tra Parigi e Marrakesh?*, «Scienze & Ricerche», 42, 1 December 2016, pp. 9-13.
- *Amare Gaia, il messaggio dell'ultima fantascienza*, «Scienze & Ricerche Magazine», April 2017, pp. 13-16.
- *La crisi delle "3 E": economia, energia ed ecologia*, «Nuova Secondaria Ricerca» (peer reviewed), with Alice Tosatto, year XXXIV, 10, June 2017, pp. 16-29.
- *"Eco-Ego". Un'immagine per rappresentare l'ecologia (profonda)*, «Scienze & Ricerche» (peer reviewed), 51, August-September 2017, pp. 14-20.
- *Lontani dal (senso del)l'equilibrio: qualche aspetto cognitivo del nostro modo di vivere nel presente*, in *Nuovi sguardi sulle scienze cognitive*, a cura di M. Cruciani e M. E. Tabacchi,
- *Narrare storie, tra didattica e divulgazione*, «Nuova Secondaria», year XXXV, 5, January 2018, pp. 23-24.
- *Le alternative per la mobilità sostenibile: il caso dell'idrogeno*, con prof. Lorenzo Battisti, «Sapere», year 84, 1, February 2018, pp. 22-27.

[1] Almost all of them are in Italian.

- *L'energia tra Cassandra, Seneca e Melville*, «Nuova Secondaria», year XXXV, 9, May 2018, pp. 74-76.
- *Peaks and Cliffs: An Example of the Power of Analogy Across Disciplines*, in «Transversal: International Journal Historiography of Science» (peer reviewed), June 2019.

- Member of the editorial board of «Scienze & Ricerche» magazine.
- Member of scientific council of «Nuova Secondaria» magazine.
- Member of the jury of the "Gianfranco Dosi" National Award for Scientific Dissemination.

## A.3.2 Public speaking in events, seminars, lessons

- *La crisi delle 3 E: Energia, Ecologia, Economia*, with prof. Claudio della Volpe, Green Week 2017, Trento, March 4th.
- *"Drill, baby, drill!" A che ora è la fine del mondo? A game on Hubbert's Peak*, with prof. Claudio Della Volpe, Bright 2017, Trento, September 9th.
- Participation in the first day of environmental sustainability at the University – Green Week 2018, with prof. Claudio Della Volpe and dr. Luca Pardi, Trento, March 17th.
- Seminar on "Communicating techniques and technology", University of Rome "Tor Vergata", as a lesson to the academic course "Theory and technique of knowledge communication", held by prof. Marco Ferrazzoli press office manager at National Research Council, a. y. 2017/2018, Rome 2018, April 17th.
- Exercise-lesson on the game of the Hubbert's Peak, SECI - University of Florence, with dr. Luca Pardi.
- Conference: *Sostenibilità circolare: limiti energetici, ecologici ed economici*, with dr. Luca Pardi, ARPA Friuli Venezia Giulia, Palmanova, Udine 2018, October 12th.
- Conference: *Renne, balene, tacchini e farfalle: lo zoo della catastrofe*, Festival della Scienza, Genova 2018, November 2nd.

## A.3.3 Other

Creation of the website presentation about Hubbert's peak game (in Italian): https://sites.google.com/g.unitn.it/gioco-del-picco/home

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[1] It has been impossible to find information on the translation of the original chapters that compose this book.

[2] The acronym stands for Greenhouse Gases Protocol Team. The report is available online at: http://www.ghgprotocol.org/files/ghgp/public/Corporate-Value-Chain-Accounting-Reporing-Standard_041613.pdf

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