Fifth International Symposiym on Energy,Puerto Rico Energy Center-Laccei, February 7-8, 2013,Puerto Rico.

Fossil fuels and energy sustainability

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ABSTRACT

In this paper we discuss the concept of net energy efficiency (Energy Return On energy Invested EROI) in general. We discuss the reality of world energy resources of oil, shale oil, gas, shale gas, and coal. For some of them (oil, gas and coal) we estimate the future of their production in tem of logistic models. We analyze the current production of shale gas.

We present detailed results for the EROI associated with heavy oil production. For steam injection the EROI is found to be in the range of 10 to 50. For electrical heating, reported field data falls in the same range when the applied energy is taken to be the maximum energy of the heaters.

We discuss the EROI for the production of methane from submarine hydrate deposits by 60Hz electrical heating (EROI = 1.7) and the EROI for or the case of thermal excitation in accordance to the Japanese scheme for the Nankay trough - EROI above 30 when the production starts, decreasing to a value of 7 after 30 years.

Keywords: fossil fuels, Energy, fossil fuels, methane hydrates, EROI, sustainability

1. INTRODUCTION

The sustainable development of the world depends critically on many variables. Among the more important variables we find: population growth, food production, global warming, and energy and water availability. In the last two decades we have been concerned with research related to energy [Callarotti 2007] and more recently with the concept of net energy balance for different production methods of heavy oil (electrical heating vs. steam injection) and in view of the large energy reserves associated with methane hydrate deposits in the world, we evaluated the energy balance (energy out / energy in) associated to the production of methane from submarine hydrate deposits by heating (Callarotti 2010) and by hot water injection (Callarotti 2011). Should this partial energy balance turn out to be less than unity, the complete EROI (Energy Return On energy Invested) would be even less than unity when the energy required for the construction, maintenance (and decommissioning) of the system is added. No additional calculation would then be required.

The concept of EROI is shown in Figure 1. Figure 1a considers the complete EROI balance where all the energies involved for the construction, operation and possible decommisioning of a system are considered.

The easier calculation is perhaphs the determination of required energy to be applied to the system in the case of petroleum, gas and methane hydrates sources. If the partial EROI thus determined turns out to be less than 1 then the particular energy producing process is untenable. If the partial EROI is greater than unity, then the other energy requirements must be evaluated so as to determine if the process is valid. Figure 1b illustrates the concept of a partial EROI less than unity, where the balance of energy only considers applied energy and where no further calculations would be required.

In the case of solar thermal or photovoltaic conversion, or in the case of wind energy, the sun supplies the free applied energy, so the EROI must be calculated taking into account all the other required energies for the construction, maintenance and decommisioning of the installation.

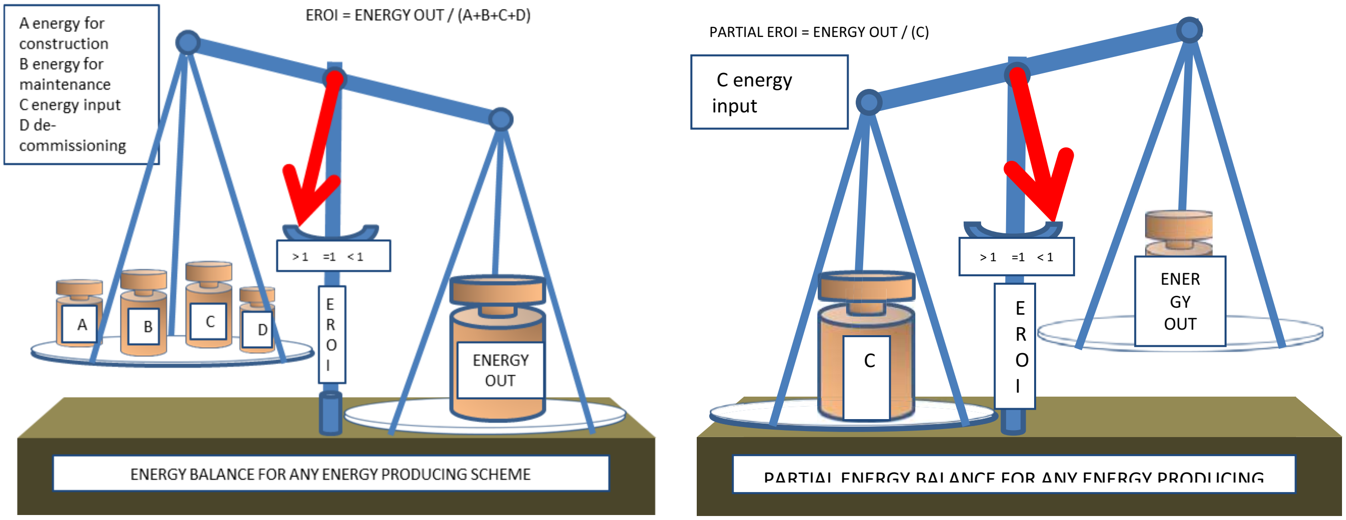


Figure 1: a) Complete EROI >1 b) PARTIAL EROI <1

The concept of net energy has been considered by several authors. In the foreword of his book on NET-Energy analysis D.T. Spreng [Spreng 1988] indicates that as a result of the energy crisis of 1974, the policies affecting energy use were being revised. He mentions that the concept of net energy analysis was considered in the US Congress Public Laws 93-577 (law since 12/31/74) and 96-264 (law since 6/30/80) which required that every governmentally sponsored scheme for producing energy should be subjected to net-energy balances: the assessment of how much energy system uses to maintain itself. In 1982 the comptroller general of the US reported to the Congress that DOE was not considering net energy yields when funding new technologies [Bowsher 1982].

The concept of EROI in the case of oil production was clearly illustrated by the words of the distinguished American geophysicist M. King Hubbert in response to David Nissen (of Exxon) indication that oil production would not be limited if sufficient money was available. Dr. Hubbert answered the following:
“Your statement that the fraction of the original oil-in-place that will be recovered is correct, but the effect may easily be exaggerated. For example, we know how to get oil out of a reservoir sand, but at what cost? If oil had the price of pharmaceuticals and could be sold in unlimited quantity, we probably would get it all out except the smell. However there is a different and more fundamental cost that is independent of the monetary price. That is the energy cost of exploration and production. So long as oil is used as a source of energy, when the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil, production will cease no matter what the monetary price may be. During the last decade we have very large increases in the monetary price of oil. This has stimulated an accelerated program of exploratory drilling and a slightly increased rate of discovery, but the discoveries per foot of exploratory drilling have continuously declined from an initial rate of about 200 barrels per foot to a present rate of only 8 barrels per foot.”

As we will discuss in the next section, M.K. Hubbert predicted in 1956 [Hubbert 1956] the peak in US oil production that would take place near 1970. This prediction was based on the application of the logistic equation that rules the production from any finite resource deposit.

In recent years one of the most important advocates for “proper” energy and the need for an EROI>1 has been Charles A.S. Hall from the State University of New York (Syracuse) [Hall et al 1992][Hall 2011][Hall and Klitgaard 2012] [Gupta and Hall 2012].

The requirement that for ANY renewable energy process (solar thermal, solar PV, hydrogen generation, wind, etc.) the EROI should be greater than 1 is of fundamental importance in order to validate the net energy generation process.

In section 2 we overview energy situation for the US and for the world. In section 3 we use the logistic equation to estimate the availability of petroleum resources in the future. In section 4 we present our conclusions.

2. FOSSIL CONVENTIONAL FUELS OVERVIEW (OIL, GAS, COAL)

In this section we will be mainly concerned with the case of petroleum.

2.1 POWER RQUIREMENTS AND WORLD POPULATION

Figure 2 indicates the time dependence of the annual power used in the world as well as the behavior of the world's population. Both have shown an exponential growth.

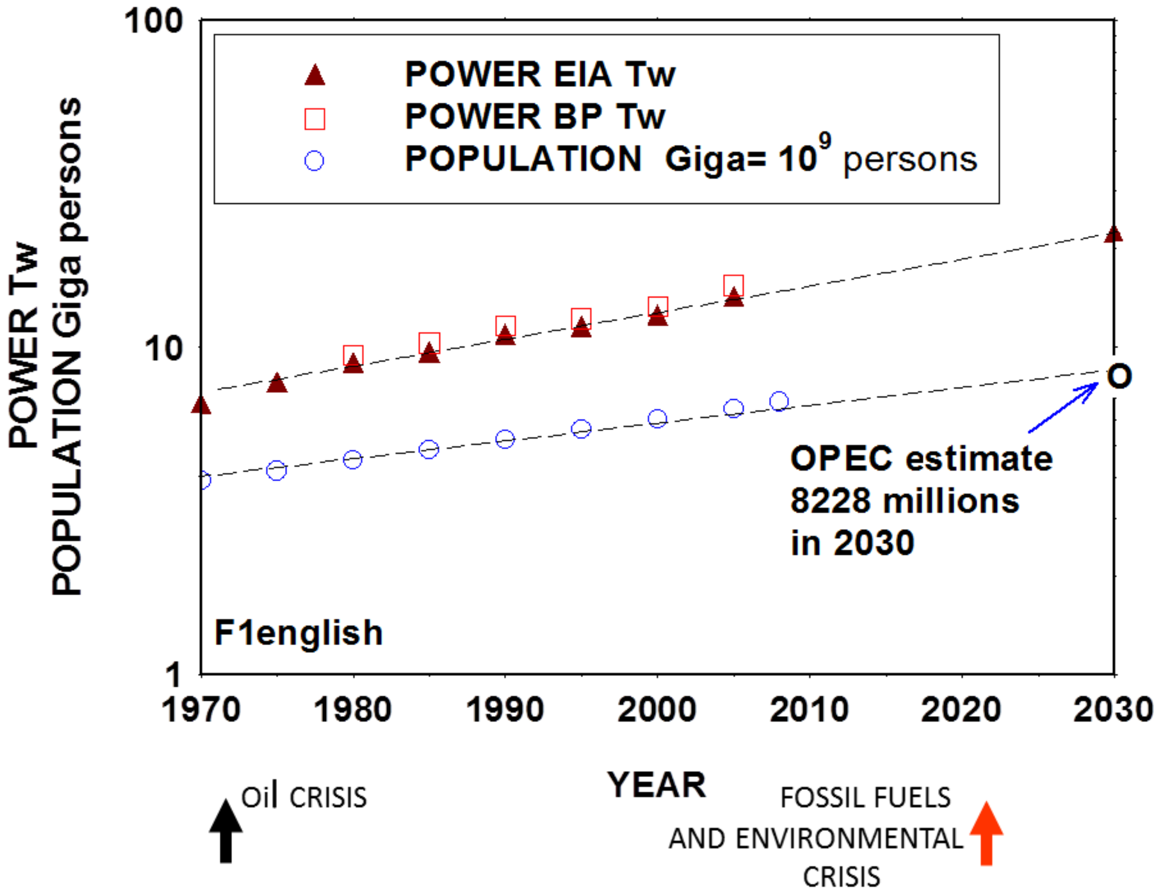
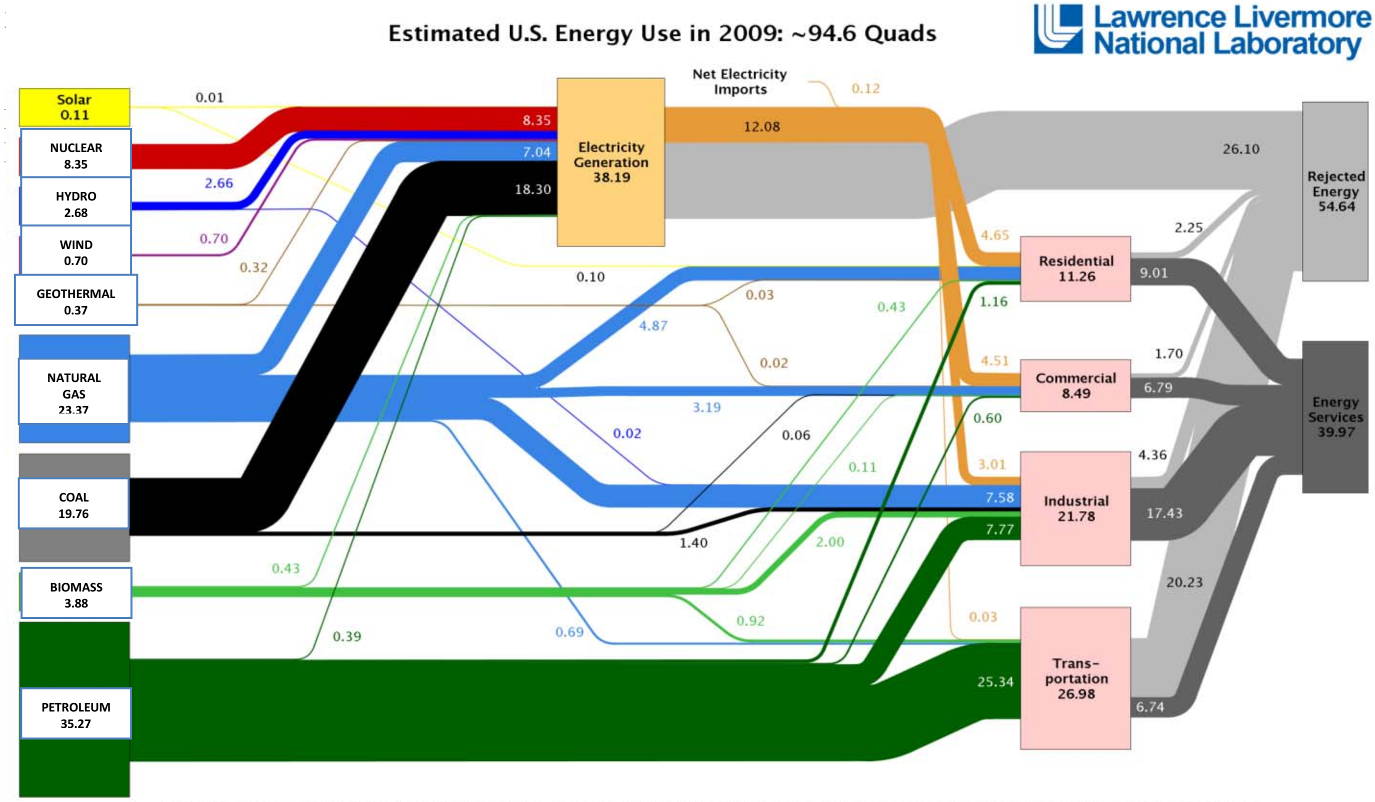


Figure 2: Power used in the world (in Terawatts and according to the Energy Information Agency – triangles, and to the British Petroleum company- squares), circles: population of the world (billions)

The present ratio of power/person is of the order of 2.4 Kw/person, estimated to grow to 2.7 Kw/person by 2030 if the present trend continues.

2.2 US ENERGY DIET

Figure 3 (DOE-EIA 2009) illustrates how the different energies are used. Several important facts are determined from the figure:
a) renewable solar and wing energies are insignificant
b) electricity is produced from coal, gas, nuclear and a little hydroelectric
c) most of the gas goes for heating (residential, commercial and industrial)
d) 54.64 quads out of the total of 94.6 quads (57.76%) is WASTED
e) most of the petroleum is required for transportation and for the industrial sector (production of plastics), the petroleum required for the production of electricity is negligible
f) the US require about 1/5th of the total world energy requirements (300 million people vs. some 700 millions)


Estimated U.S. Energy Use in 2009: ~94.6 Quads

Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 3: Energy distribution chart for the US in 2009 (from DOE/USEIA)

Most of the wasted energy is due to the 31.6 % overall efficiency for the production of electrical energy and the 25 % efficiency for the use of petroleum in transportation. If all the ground vehicles were to be converted to electrical traction, the added electricity requirement would have to be satisfied with added coal (CO2 contaminating) production or with nuclear energy. Alternate energy sources (wind and solar) are obviously not constant, thus the requirement for a very efficient electrical grid distribution system that should be able to compensate the variations with sufficiently fast responses. New developments in satellite synchronized phase measurements might be useful in the achievement of an efficient smart grid. An additional element for the possible intelligent use of wind and solar photovoltaic systems is their EROI. Reported values for wind generation show EROI values greater than 1 although this is variable depending on the system structure. The situation is more complex in the case of PV generation.

In view of the space limitations for this article we will discuss in detail only the case of oil production. As we mentioned above, using the concepts of the depletion theory for finite supplies, in 1956 M.K. Hubbert predicted that the petroleum production for the lower 48 states would peak around 1970. Figure 4 show the accuracy of Hubbert's prediction for US oil production.

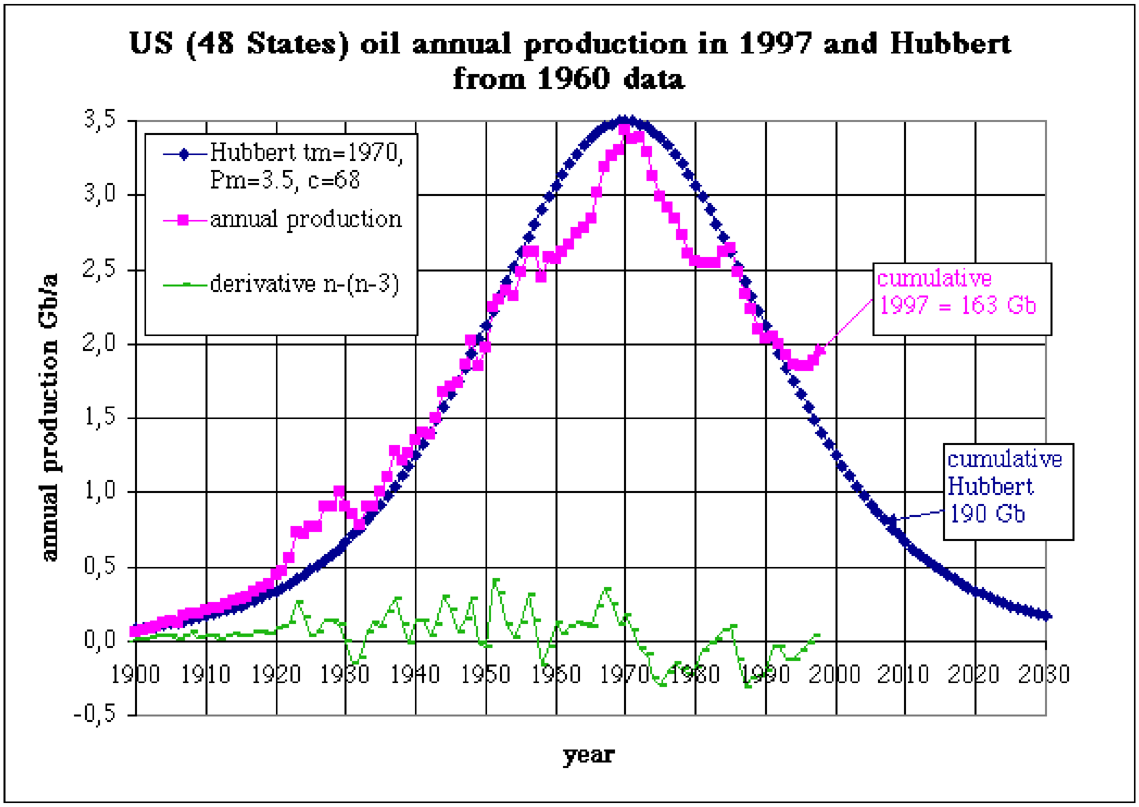


Figure 4: Hubbert 1960 prediction vs actual US (lower 48 states) annual oil production

In Table 1 we show oil production for the US in the recent years[USEIA 2012] . The table shows the increase of the last years (mainly due to the Eagle Ford formation in Texas and to the Bakken Shale formation in North Dakota). Most of the increase is due to production by means of hydraulic fracturing (fracking). It is not clear what the EROI is for this process. What is known is that in the case of gas production by fracking (gas shale), there are several unanswered questions regarding the possible environmental effects due to the chemicals that are added to the water that is injected at high pressures, and the possible effects of the reservoir fractures.

In any case the fact remains that production has increased. In a Wall Street Journal article which appeared on December 4, 2012 on page B2 (US edition), Tennille Tracy states "The US oil boom has some limitations. Fracking relies on relatively high oil prices to be economical, while producers such as Saudi Arabia have access to huge resources of cheap oil. The International Energy Agency predicted that after 2020, Saudi Arabia and other OPEC members will control a larger share of the global oil market."

Table 1: US OIL PRODUCTION DURING THE RECENT YEARS

Year	1999	2001	2003	2005	2007	2009	2011
Production Gb/year	2.14	2.12	2.07	1.89	1.850	1.95	2.07
% annual change	-5.92	-0.35	-1.13	-4.44	-0.74	+8.29	+3.52

According to the US Energy Information Administration, the US imports of crude oil have decreased some 10% in the period from January 2007 to December 2011, from a level of some 3.65 Gb/year to some 3.29 Gb/year.
On November 2012 Reuters reported that US oil imports in September were down from a year ago by 539,000 BBL per day. The US Energy Information Administration said that crude imports averaged 8.375 million BBL per day in September. Imports of crude oil have dropped year-over-year in eight of the first nine months of the year. The dip in imports coincided with a decline in U.S. oil demand in September, down 3.81 percent from a year ago.

2.3 WORLD OIL RESERVES

The data shown in Table 2, was used in a British Petroleum presentation of March 2011 "Heavy oil vs. light oil" which classifies world resources in terms of conventional oil, heavy oil, and extra heavy oil and bitumen.

Table 2: OIL RESERVES

Type of oil	Conventional	Heavy	Extra heavy and bitumen
% of reserve	30	15	55

As heavy+extra heavy and bitumen represent some 70% of the total, it is important to understand the differences between heavy oil, extra heavy oil, bitumen, oil sands and oil shales. Table 2 might help.

Table 3: TOTAL OIL RESERVES PROJECTIONS

CLASS	Medium Heavy Oil	Extra heavy oil	Tar Sands and Bitumen	Oil Shales
API density	25 to 18	20 to 7	12 to 7	solids
Viscosity range centipoises	100 to 10 cpo	10,000 to 100 cpo	> 10,000 cpo	solids
Mobility at reservoir conditions	MOBILE	MOBILE	NON MOBILE	NON MOBILE

The EROI for each class will vary greatly. Obviously the worst EROI will correspond to Oil Shales since this process implies essentially rock mining followed by heating. The organic material is kerogen (an earlier precursor of oil) that must be distilled in order to have oil. Oil from shales was a production technique used in Europe in the early 1900's but was discontinued thereafter.

Extra heavy oil (API density <10) is mobile (in the case of the Faja del Orinoco deposits in Venezuela) where it can be produced by submersible electrical pumps and by progressive cavity pumps and extended networks of horizontal wells with maximum contact to the reservoir. This is so because the temperature at reservoir depths is high enough for the crude to be mobile. Furthermore, electrical heating combined with submersible pumps (a down hole heater excited by the same high voltage applied to the motor that excites the pump) can lead to very significant production improvement. In the case of the extra and heavy oil near lake Maracaibo basin, the most production (in vertical wells) has been carried out by heating via cyclic steam injection, although down hole electrical heaters have been tested.

The EROI values for cyclic steam injection results for the Maracaibo basin and for low frequency (6o Hz) electrical heating production in the world are summarized in Figure 5 [Callarotti 2003]. They are in the 10 to 50 range. The results for the EROI for the electrical heaters are underestimated, as they were obtained considering the reported maximum heater power although some of the heaters were operated at variable power levels in order to maintain a given heater temperature. Steam injection has shown to be efficient, but: it requires water, can be repeated only a few times (as too much water will be produced with the crude), it is unsuitable for shallow reservoirs and requires a wide pipe distribution net for the steam to reach from the generating unit to each well. As each well is already connected to the electrical grid (for the 60 Hz 440 volt tri-phase excitation of the pump jack motors), electrical heating is very convenient since it only requires the additional down hole heaters.

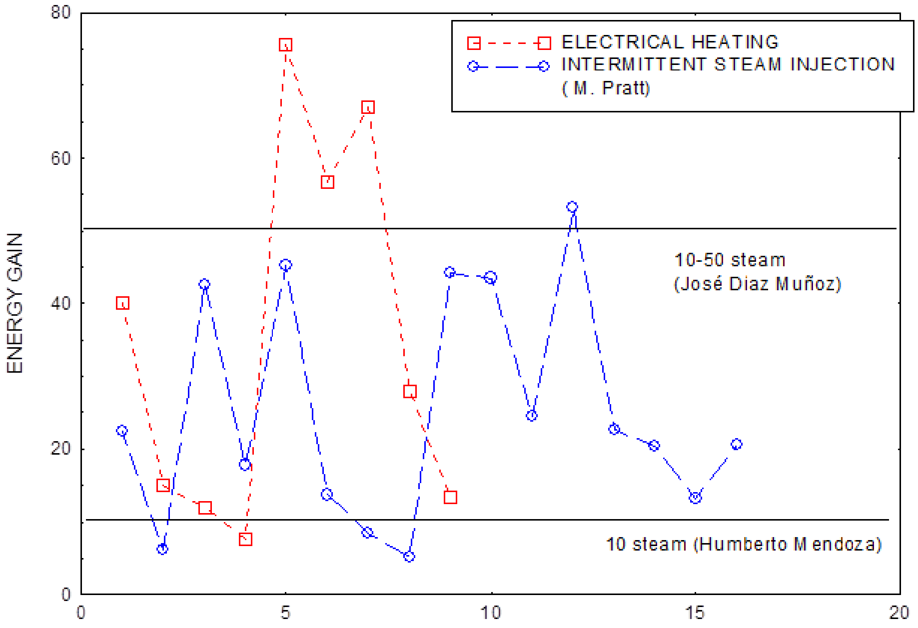


Figure 5: Energy gain (EROI) for cyclic steam injection (Circles) (846 wells in the Tia Juana region and 231 wells in the Lagunillas fields) and for 9 low frequency electrical heaters (squares) placed in the US, Chine, Venezuela, and Canada. The horizontal lines indicate the estimates given by PDVSA petroleum engineers Munoz and Mendoza.

3. LOGISTIC EQUATION

The Verhulst logistic equation (VLE) relates the annual P(t) production of a given product (for example millions of tons of oil equivalent per year: MTOE/year), with X(t) the total annual production obtained since the production started (MTOE). Q_∞ is the maximum amount available of a given product (MTOE) and Q(t) is the amount of product which has yet to be produced by the year t (MTOE).

$$P(t)=\frac{dX(t)}{dt}=-\frac{dQ(t)}{dt}=\frac{k(t)Q(t)}{n}\left[1-\left(\frac{Q(t)}{Q_\infty}\right)^{n}\right] \tag{1}$$

$$X(t)=\int_{-\infty}^{t}P(t)\,dt=-\int_{-\infty}^{t}\frac{dQ(t)}{dt}\,dt=Q_\infty-Q(t) \tag{2}$$

$$Q(t)=Q_\infty-X=Q_\infty-\int_{-\infty}^{t}P(t)\,dt \tag{3}$$

The case n=1 corresponds to the equation used by Hubbert. The VLE solutions for the case where k is a constant are:

$$P(t)=\frac{k\,Q_\infty}{n}\frac{(2^n-1)\exp\{k(t-t_{1/2}\}}{\left[1+(2^n-1)\exp\{k(t-t_{1/2}\}\right]^{(1+\frac{1}{n})}} \tag{4}$$

$$Q(t)=\frac{Q_\infty}{\left[1+(2^n-1)\exp\{k(t-t_{1/2}\}\right]^{\frac{1}{n}}} \tag{5}$$

Where $t_{1/2}$ was defined in such a way that at this value of time half of the available product has been produced or – equivalently – half of the available product is left to be produced.

$$Q(t_{1/2})=\frac{Q_\infty}{\left[1+2^n-1\right]^{\frac{1}{n}}}=\frac{Q_\infty}{2} \tag{6}$$

If we plot Y(t) vs X(t):

$$Y(t)\equiv\frac{P(t)}{\int_{-\infty}^{t}P(t)\,dt}=\frac{P(t)}{X(t)} \qquad\qquad X(t)\equiv Q_\infty-Q(t) \tag{7}$$

$$Y=\frac{k}{n}\frac{\dfrac{(2^n-1)\,\exp\left[k(t-t_{1/2})\right]}{\left\{1+(2^n-1)\exp\left[k(t-t_{1/2})\right]\right\}}}{\left[\left\{1+(2^n-1)\exp\left[k(t-t_{1/2})\right]\right\}^{(1/n)}-1\right]} \qquad X=Q_\infty\left[\frac{\left\{1+(2^n-1)\exp\left[k(t-t_{1/2})\right]\right\}^{(1/n)}-1}{\left\{1+(2^n-1)\exp\left[k(t-t_{1/2})\right]\right\}^{(1/n)}}\right] \tag{8}$$

We have shown [Callarotti 2008] that in the limit when the production begins:

$$Y_n\cong k\left[1-\frac{nX}{Q_\infty}\left\{1+\frac{1-n}{2n}\right\}\right] \qquad\qquad Y_{n=1}=k\left[1-\frac{X}{Q_\infty}\right] \tag{9}$$

As shown in Figure 6, from the plot of Y (Production/integral of the production) vs. X (the integral of the production, for the initial times of production), from the above equation we can either determine Q∞ if n is known, or vice-versa. The initial slope of the semi-log plot for production vs. time allows the determination of k , which is independent of n. This is shown in Figure 6.

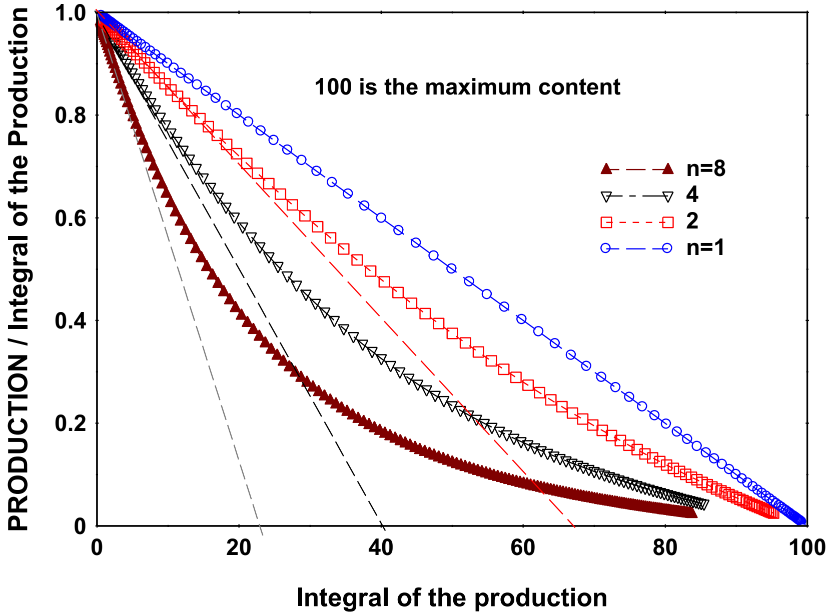


Figure 6: Ratio of production divided by its integral vs. the integral of production

For the estimated Verhulst projection we used 6 Tera barrels for the total amount of conventional and non conventional oil deposits. The results of our projected oil curve are shown in Figure 7 where they are compared with projections of the Department of Energy (DOE). Our model predicts a peak in 2038.

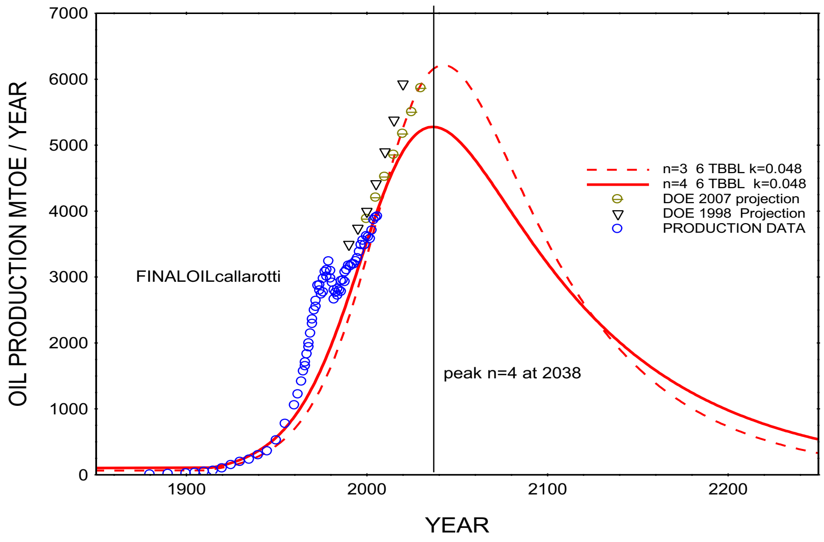


Figure 7: Prediction of the production of oil (conventional and heavy)

Our estimate of the 6 TBBL total available oil was influenced by the recent U.S. Geological Survey report [USGS 2009] released on 1/22/2010. A new US assessment of Venezuela's oil reserves could give that country twice the supplies of Saudi Arabia. The USGS team gave a mean estimate of 0.5513 Tera barrels of "technically recoverable" oil in the Orinoco belt - the estimate was based on oil recovery rates of 40% to 45% and considered heavy and extra heavy oil. Canada's reserves (heavy and extra heavy) are of the order of 0.310 TBBL, while Saudi Arabia's (light and medium) are of the order of 0.260 TBBL.

4. CONCLUSIONS

Petroleum, as gas and coal, will no longer be produced when the EROI for the different production methods will decrease below unity. Energy requirements will increase as the population of the world increases, and these needs will increase at a faster rate in developing countries (mainly India and China). EROI values for renewable energy sources MUST be carefully evaluated in order to ensure their sustainability. EROI values should be cited by governments and by companies. This is not the case at present.

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