The Hill's Group
Mining & Manufacturing Engineering

A reserve status report
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Depletion: A determination for the world's petroleum reserve

An exergy analysis employing the E_{TP} model

Abstract:

Petroleum is a primary energy source; its other uses have only minor commercial value. It therefore follows that to be an energy source petroleum must be capable of providing sufficient energy to support its own production system (extraction, processing and distribution). Thus, the total specific (per unit) energy needed to complete the process can not exceed its own specific exergy. Entropy production (*a Second Law mandate*) in the petroleum production system (**PPS**) requires that a point will to be reached when the production energy required to drive the process forward becomes equal to its specific exergy. It can be shown that this breakeven point for petroleum production occurs when the cumulative production curve approaches its top abscissa. This point represents the maximum theoretical volume of petroleum that can ever be extracted for use as an energy source. The total production energy (**E_{TP}**) is therefore a function of the cumulative production function (**CPF**) and the entropy production of the **PPS.** The entropy production of the **PPS** is derived through the solution of the *Entropy Rate Balance Equation for Control Volumes*. The **E_{TP}** function generated is an accurate predictor of historic and future petroleum prices, production, and the depletion status of the world's petroleum reserve.

1.0 - Introduction:

The history of resource depletion is as old as the history of mankind. Depletion is the inevitable consequence of resource extraction, and falls into the same category as death and taxes. The Emperor Constantine in 340 AD[1] was forced to mint a gold coin, the Solidus, as a substitute for the silver coinage of the Roman Empire. Depletion at their Rio Tinto mines in Iberia had reduced the output of their primary source of silver. Coal extraction from surface operations in Britain, which began in the second century AD, came mostly to a conclusion in the 1990's when the majority of their mines became too deep and veins too narrow to continue operations. Depletion has taken its toll with these, and with many other minerals throughout time.

Today we face the advancing depletion of another vital resource. It is demonstrating this with characteristic symptoms: declining or stagnated production, rising price, declining quality, and fierce competition for remaining reserves. Conventional crude production has not increased since the mid 2000's, its price has increased over 450% in a decade, and we are getting continual reports that vast sums of money are being earmarked for reserves that only a few decades ago where considered to be of little value by the industry. Refineries are being re-engineered to process heavier, metallically contaminated, and high sulfur crude. Petroleum is displaying typical symptoms of latter stage depletion.

Determining the depletion state of a resource is, however, not merely a matter of determining how much of the resource remains in the ground. Rio Tinto's deposits still contain considerable amounts of silver, and we hear frequent reports of attempts to re-open old mine sites or start new ones. British citizens are undoubtedly still walking over huge deposits of coal. A resource's depletion state has as much to do with the efficiency with which it can be extracted and used as it has to do with the quantity of resource remaining in the ground. To define oil's depletion state it is necessary to look at the efficiency with which crude oil can be extracted, processed, and used. Therefore it is necessary to understand why petroleum is produced, and then be able to analysis the entire production process; not just the extraction portion. The Quality Control Engineer defines this as determining "fitness for use". To define crude oil's depletion state we must first determine the quantity of it that is "fit for use".

Optimistic estimates place the initial world oil reserve at 4.3[2] trillion barrels, of which 1.29 trillion have been extracted. If quantity were the sole criteria for utility there would be little question as to the availability of future supplies; there would obviously be several centuries of potential crude remaining. Individual field studies, and the ever escalating costs of oil production are, however, informing us that something is amiss with the strict quantity model; it fails to incorporate a verifiable "fitness for use" criteria.

Most studies of world oil production are focused on the rate at which crude oil is extracted, and the volume that remains to be removed . Since petroleum is used primarily as an energy source to drive the majority of the world’s transportation machinery, the quantity of oil available for extraction would only be significant if over time a unit of it provided the same amount of energy for that purpose. The *Second Law* informs us that can not be the case; in fact, every barrel of oil *on average,* has required more energy to extract and process than the barrel that came before it. This is an inviolable mandate of the *Second Law.* Since the specific exergy of a unit of oil is, and always has been the same, less and less energy per unit remains for use by the end consumer. The "fitness for use" of crude oil must also then be dependent on variables relating to its energy delivery capabilities.

Evaluations of reserve status generally rely on top-down, or bottom-up analysis. This approach requires knowledge of the production history of individual fields and their physical parameters; which are often scanty, inaccurate, or unavailable. It also requires questionable future projections for an oil price that can justify the economics of the production process. The only high quality data available relating to the world's crude oil reserves is the quantity of conventional crude oil that has been produced, and its price history. To overcome these limitations ***the entire production process (****extraction, processing and distribution****) is analyzed.*** Fitness for use is built into the methodology. Correlation is checked against the world production, and price data-sets. Causation is established through its bases in *First* and *Second Law* premises.

Although qualitative indicators point to the world's oil reserves being in an advanced stage of depletion, the investor/planner needs more than qualitative reports about the petroleum depletion event. They need quantitative estimates about what to expect from its price and availability over a period great enough to plan and execute a project. With capital difficult, and expensive to procure an energy *surprise* has gained the capacity to place many projects, that would have otherwise excelled, over budget and behind schedule. The scope of any project of significant duration can not today be effectively ascertained without considering the potential impact of the depletion of our most widely used and efficacious commodity. **D*epletion: A determination for the world's petroleum reserve*** provides the planner and astute investor with the specific information they will need to define and effectively pursue their objectives!

Petroleum is defined as "rock oil", or conventional crude API 30 - 45°. Other forms of hydro-carbons, such as bitumen, are not included in this definition. The terms crude oil and petroleum will be synonymous throughout this report.

The English Engineering system which employs the lb mass, ft length, second time and lbf force as its primary units, in conjunction with Field Units and Darsie Units are the prevalent systems used by the petroleum industry. We adhere to those systems throughout this report [3].

1900 is year zero (0) in all graphs and equations, unless otherwise noted.

2.0 - Theory:

Definitions:

E_G - *Gross Exergy:*

The specific exergy of one US gallon (231 cubic inches) of crude oil. API 35.7° crude delivers 140,000 BTU per gallon (see **7.0 - 2**): *BTU/gal*

E_N - *Net Energy:*

The specific energy of one US gallon after the work input at the well head has been subtracted. It is calculated from Equation #1: *BTU/gal*.

E_P - *Production Energy:*

The work input at the well head. It is calculated from Equation #2: *BTU/gal*.

E_D - *Deliverable Energy:*

The energy delivered to the non-energy goods (**NEGs**) producing sector of the economy. It is the *Gross Exergy* less the energy utilized by the *Petroleum Production System* (**PPS**). The **PPS** is where the energy from oil is converted into the work necessary to produce the crude and its products. It is calculated from Equation #5: *BTU/gal*.

E_{Tp} - *Total Production Energy:*

The total work required to extract, process and distribute one gallon of crude oil: *BTU/gal*.

η - *Thermal Efficiency:*

The efficiency with which the *Petroleum Production System* (**PPS**) converts the energy from oil into the work necessary at the well head to produce it. It can be calculated from Equation #6.

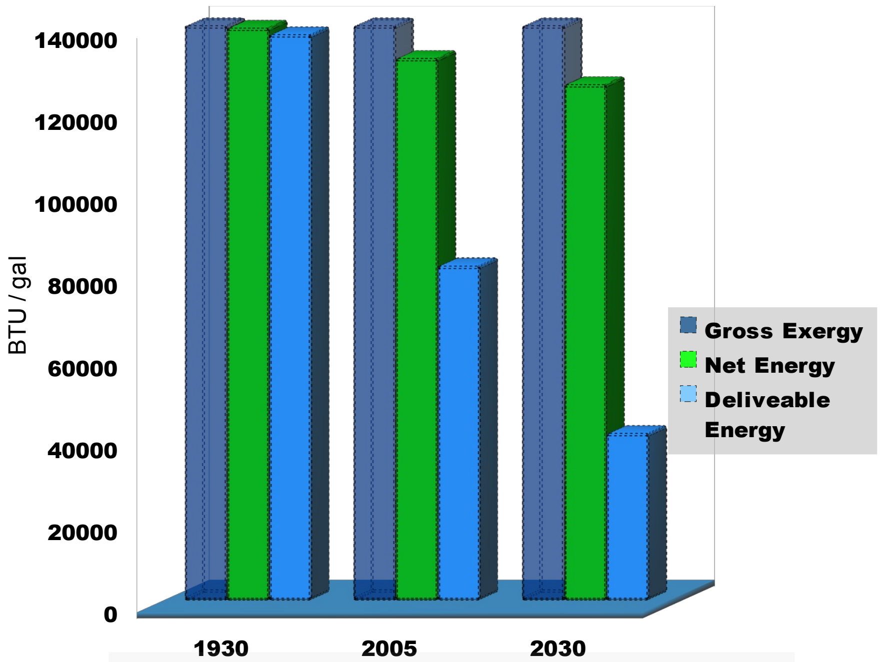
ERoEI - ***E**nergy **R**eturned on **E**nergy **I**nvested:*

The *Gross Exergy* divided by the *Production Energy* (at the well head). It is calculated from Equations # 3 and 4. **ERoEI** is often expressed using the diacritical mark ":", such as 20:1. In the equations of this report it is used fractionally, e.g. $\frac{20}{1}$ and is expressed as a real number; e.g. 20.

N_P - *The Cumulative Production at year* = # (billions of barrels, G*b*)

P_{140} - *The Maximum Total Cumulative Production:*

The maximum cumulative production that can ever be attained utilizing only oil's own specific exergy, E_G, (billions of barrels, G*b*).



Exergy in a gallon of crude, API 35.7°

Graph# 1

Equations:

1) $E_N = [1 - ERoEI^{-1}] * E_G$ BTU/gal

2) $E_P = E_G - E_N$ BTU/gal

3) $ERoEI = \left[1 - E_N / E_G\right]^{-1}$ at the well head, dimensionless ratio

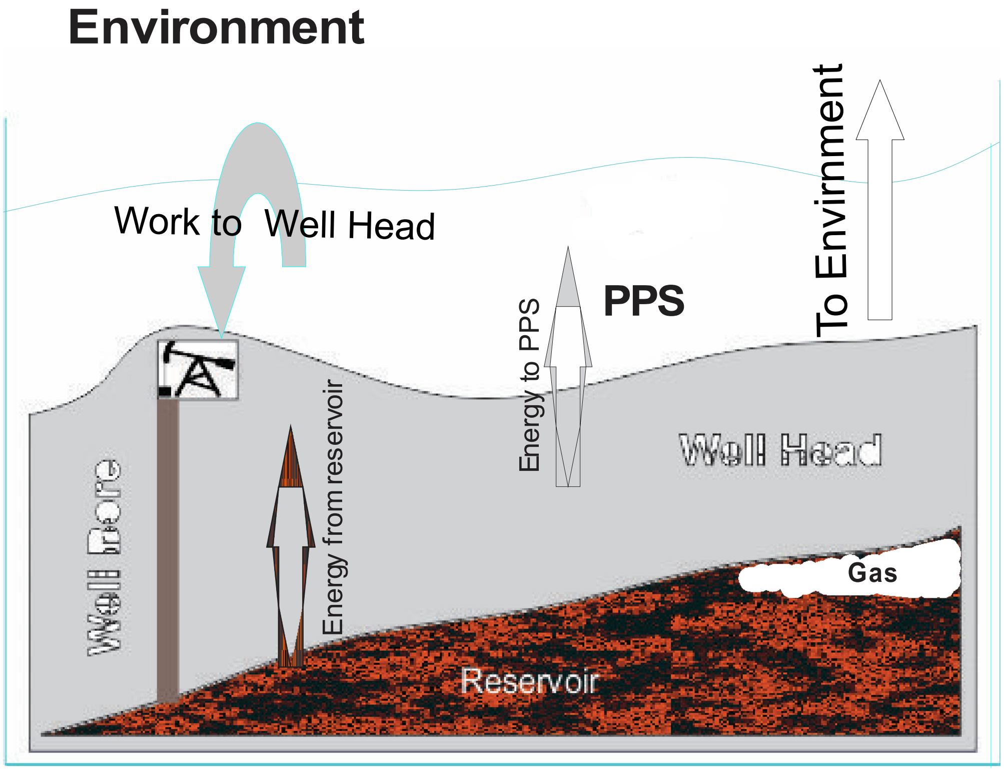
4) $ERoEI = E_G / E_P$ at the well head

5) $E_D = E_G - [E_P / \eta]$ BTU/gal

6) $\eta = E_G - E_N / E_G - E_D$ dimensionless ratio

3.0 - The Model:

Crude oil is used primarily as an energy source; its other uses have only minor commercial value. To be an energy source it must therefore be capable of delivering sufficient energy to support its own production process (extraction, processing and distribution); otherwise it would become an energy sink, as opposed to a source. The Total Production Energy ($\mathbf{E_{Tp}}$) must therefore be equal to, or less than $\mathbf{E_{G}}$, its specific exergy. To determine values for $\mathbf{E_{Tp}}$ the total crude oil production system is analyzed by defining it as three nested Control Volumes[4] within the environment. The three Control Volumes (where a control volume differs from a closed system because it allows energy and mass to pass through its boundaries) are the reservoir, the well head, and the Petroleum Production System (**PPS**). The **PPS** is where the energy that comes from the well head is converted into the work required to extract the oil. The **PPS** is an area which is distributed within, and throughout the environment. It is where the goods and services needed for the production process originate. This boundary make-up allows other energy, and mass transfers to be considered as exchanges, such as natural gas used in refining, electricity used in well pumping, or water used for reservoir injection. The boundary conditions are shown in *Diagram #1*.

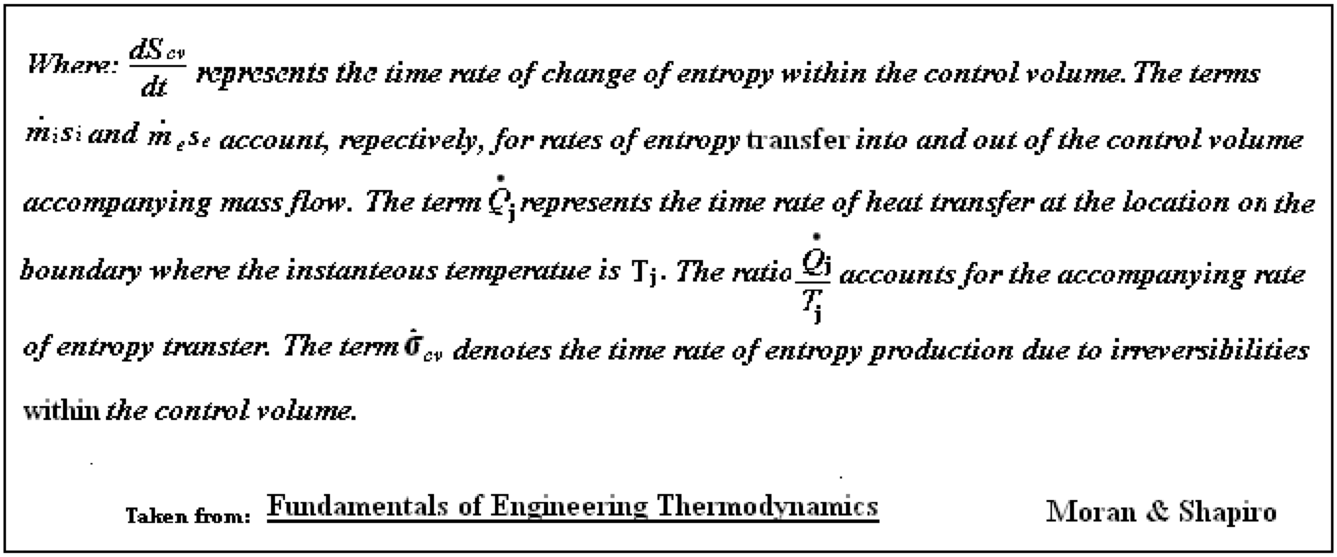


Boundary conditions and energy, work flow.
Diagram# 1

3.1 - The $\mathbf{E_{Tp}}$ Model:

Values for $\mathbf{E_{Tp}}$ are derived from the solution of the *Second Law* statement, the *Entropy Rate Balance Equation for Control Volumes:*[5]

$$\frac{dS_{CV}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{cv}$$



Where: $\frac{dS_{cv}}{dt}$ represents the time rate of change of entropy within the control volume. The terms $\dot{m}_i s_i$ and $\dot{m}_e s_e$ account, repectively, for rates of entropy transfer into and out of the control volume accompanying mass flow. The term $\dot{Q}_j$ represents the time rate of heat transfer at the location on the boundary where the instanteous temperatue is T_j. The ratio $\frac{\dot{Q}_j}{T_j}$ accounts for the accompanying rate of entropy transfer. The term $\dot{\sigma}_{cv}$ denotes the time rate of entropy production due to irreversibilities within the control volume.

Taken from: Fundamentals of Engineering Thermodynamics Moran & Shapiro

A dot above a quantity signifies a time rate of change

There is only one temperature boundary, which is at the exit point of the reservoir, and there is no crude entering the reservoir from the environment. So the equation reduces to:

$$\frac{dS_{CV}}{dt} = \frac{\dot{Q}_j}{T_j} - \dot{m}_e s_e + \dot{\sigma}_{cv} \qquad \frac{BTU}{sec * {}^\circ R}$$

Since crude oil and water can be considered as incompressible substances for this application their specific entropy's (s_C and s_W) are only affected by a change in temperature.

For specific heats: $c_V = c_P = c$, and $s_2 - s_1 = c * \ln \frac{T_2}{T_1}$ The reservoir temperature is constant so the entropy of the reservoir (S_{CV}) must be decreasing (negative in sign) at the same rate that entropy is transferred by mass flow from the reservoir. The temperature of the mass transporting s_e is the same within the reservoir as at the exit boundary . The exit boundary is were the well bore enters the reservoir. Therefore, as dS_{CV}/dt and $\dot{m}s_e$ ($dS_{CV}/dt \rightarrow 0$ as $\dot{m}s_e \rightarrow 0$) must cancel, and the heat leaving the reservoir is negative in sign, the equation becomes:

$$\frac{\dot{Q}_j}{T_j} = \dot{\sigma}_{cv} \qquad \frac{BTU}{sec * {}^\circ R}$$

The rate of entropy production in the PPS is equal to the rate of heat extracted from the reservoir divided by the reservoir temperature.

The rate of irreversibility production in the **PPS** therefore becomes:

$$\dot{I}_{cv} = T_O * \dot{\sigma}_{cv} \qquad \frac{BTU}{sec}$$

Where T_O equals the standard reference temperature of the environment, 537 °R (77° F).

Therefore:

$$E_{TP} = \int_{t1}^{t2} \dot{I}_{CV}\, dt \qquad BTU$$

Because the mass removed from the reservoir is limited to crude oil and water, the increase in $\mathbf{E}_{Tp}$ per billion barrels (Gb) of crude extracted as $ds = c\frac{dT}{T}$ is:

$$\frac{E_{TP}/lb}{Gb} = \left[\frac{(m_c * c_c + m_w * c_w)(T_R - T_O)}{m_c}\right]/Gb$$

Equation #7

giving: *BTU/lb/Gb* *where*: $0 \leq \mathbf{E}_{Tp} \leq \mathbf{E}_G$

m_C = mass of crude, lbs.
c_C = specific heat of crude, BTU/lb °R
m_W = mass of water, lbs.
c_W = specific heat of water, BTU/lb °R
T_R = reserve temperature, °R
T_O = standard reference temperature of the environment, 537 °R
si = specific entropy into the control volume
s_e = specific entropy exiting the control volume

BTU/gal/Gb for 35.7° API crude = BTU/lb/Gb * 7.0479 lb/gal[6]

3.2 - Determination of reservoir mass flow rate:

The calculation of $\mathbf{E}_{\mathbf{Tp}}$ at time (t) requires the rate of crude, and water mass flow. The rate that crude leaves the reservoir is derived from the construction of the cumulative production curve. Note that this curve is the CDF (cumulative distribution function) of the production data-set. It is the parent of what is known as *Hubbert's Curve*, which is its first derivative (PDF). ***1900 is year zero (0) in all graphs, unless noted.***

The cumulative production function is a family of logistic curves. The height of the top tail is controlled by the bottom tail (1900-1959 red and blue dots). Shown in *red* is the Campbell-Leharrère[7] 1900-1959 estimated cumulative world production, *blue* the ***Hill's Group*** determination. Both curves use 1960-2009 EIA production data

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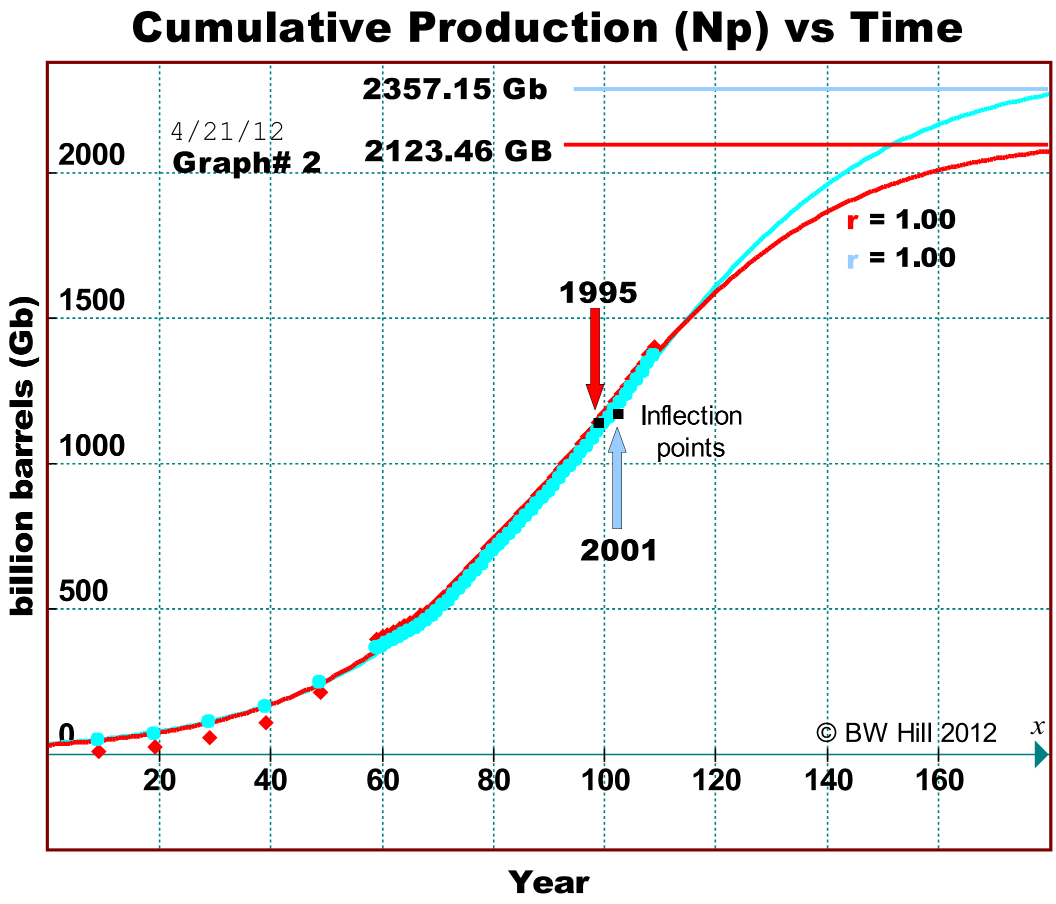

Graph# 2

The Campbell-Leharrère curve is asymptotic to the line 2123.46 Gb; the ***Hill's Group*** 2357.15 Gb. The asymptotic line for the individual curves represent $\mathbf{P}_{\mathbf{140}}$, the maximum quantity of crude oil that can ever be extracted utilizing only it own specific exergy, $\mathbf{E}_{\mathbf{G}}$. The Campbell-Leharrère curve reached its inflection point (midpoint) of 1061.73 Gb in April of 1995; the ***Hill's Group*** reached it at 1178.58 Gb in June of 2001.

The form of the cumulative production distribution is identified through the construction of its Identification Plot[8] (which uses a methodology similar to a QQ Plot). *Graph# 3* demonstrates that the cumulative production curve is well represented by a logistic function. The Identification Plot tests for the linearity of the equation produced from the quantile logistic function; z = ln(p/q). Where z represents cumulative production in billion barrels (Gb), p = (r-0.5)/n; q = 1-p. The *blue* is the 1960-2009 EIA data-set; r = 0.947. The ***black*** is the Campbell-Leharrère data-set from 1900-1959, *plus* the EIA data-set from 1960-2009; r = 0.979.

The long tails indicate that there may be some skewness in the logistic distribution.