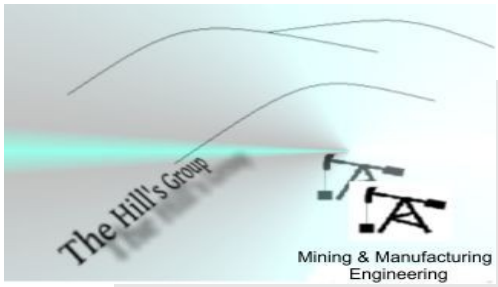


A reserve status report

Report# HC3-433

Version 2

March 1, 2015

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.

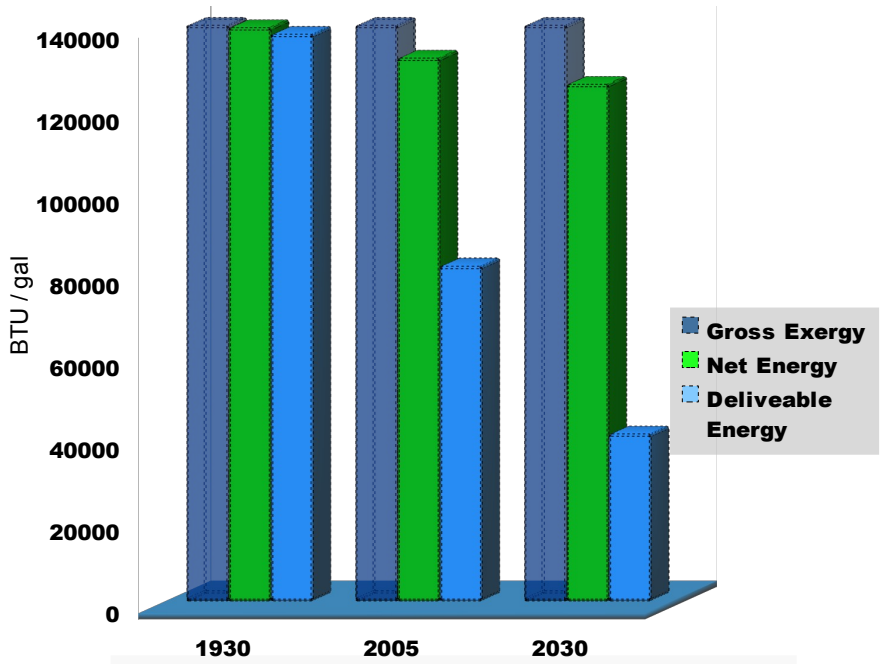
ERoEI - ***E**nergy **R**eturned on **E**nergy **I**nvested:*

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, $\mathbf{E}_G$, (billions of barrels, G*b*).



Graph# 1

Equations:

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

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

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

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

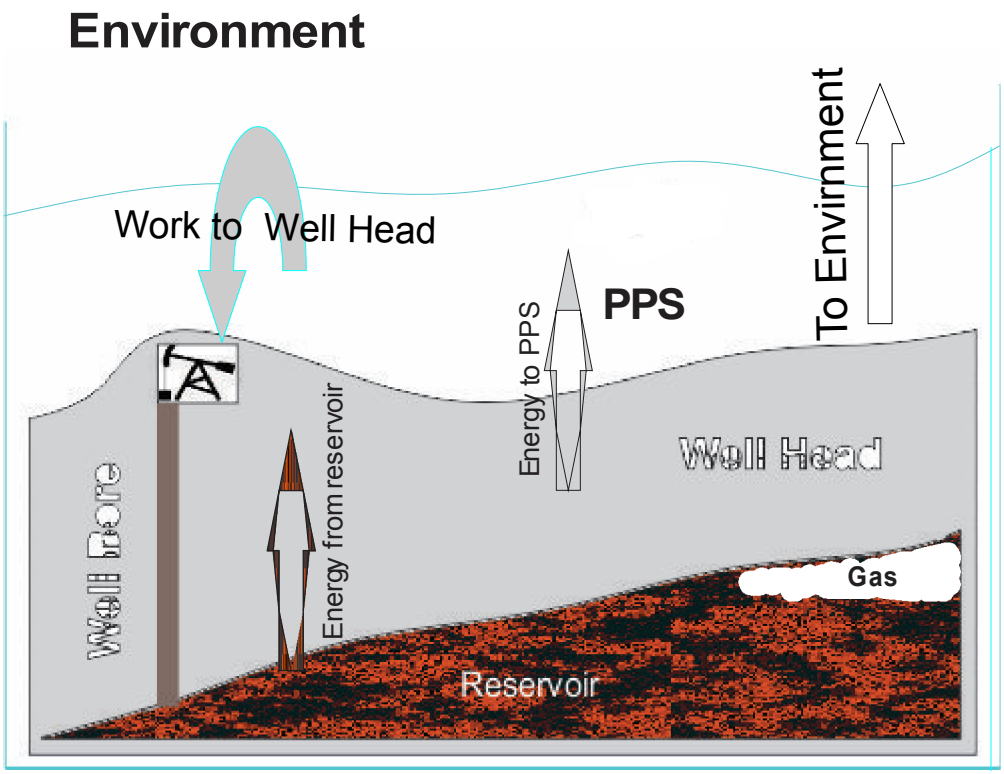
5) $E_D = E_G - [E_P / \eta]$ BTU/gal

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 transter. 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:

$$\frac{E_{TP}/lb}{Gb} = \left[\frac{(m_c * c_c + m_w * c_w)(T_R - T_O)}{m_c}\right] /Gb \qquad \text{Equation \#7}$$

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 E_{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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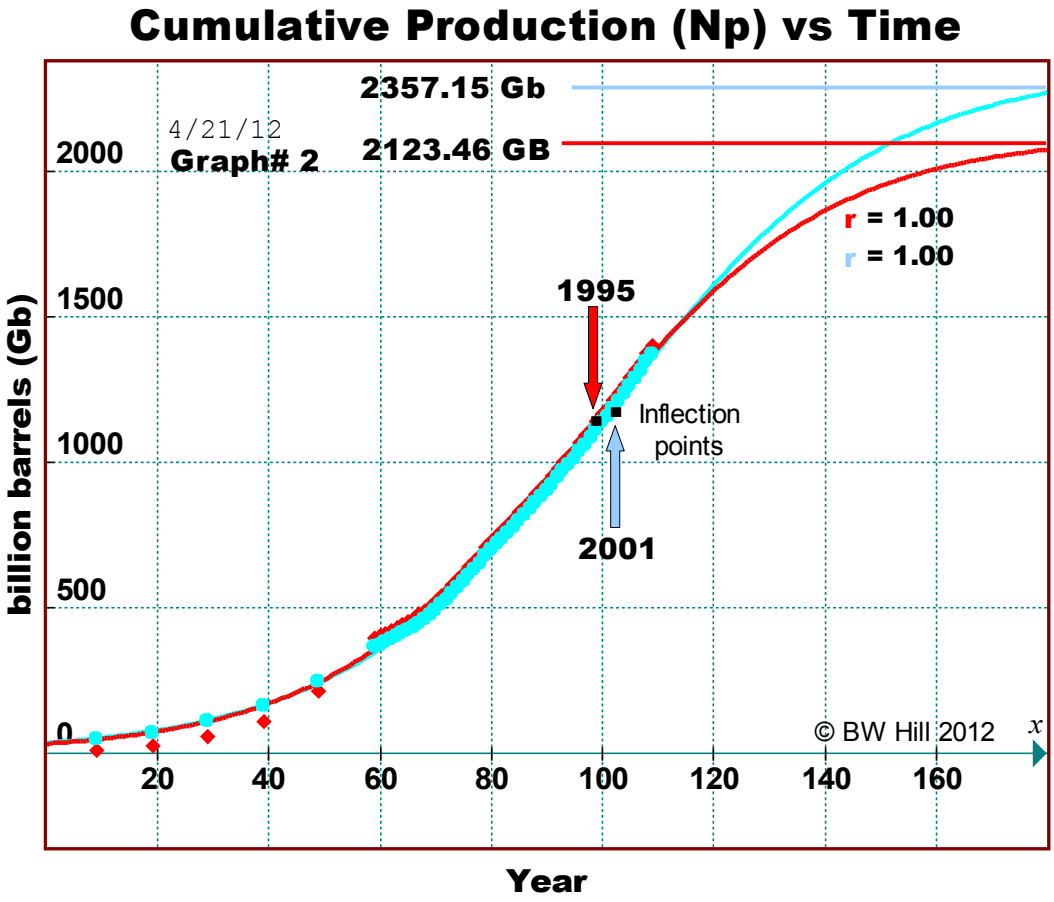


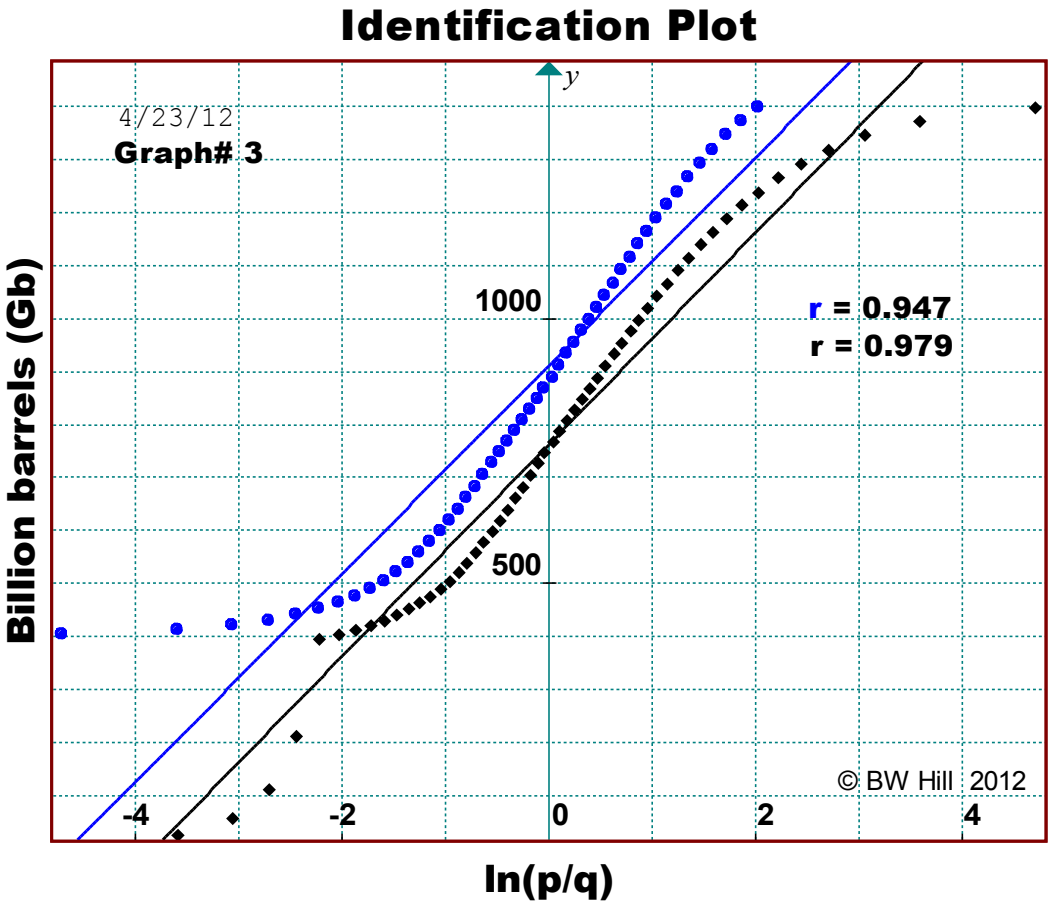
Graph# 2

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 $\mathbf{P_{140,}}$ the maximum quantity of crude oil that can ever be extracted utilizing only it own specific exergy, $\mathbf{E_{G.}}$ 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.

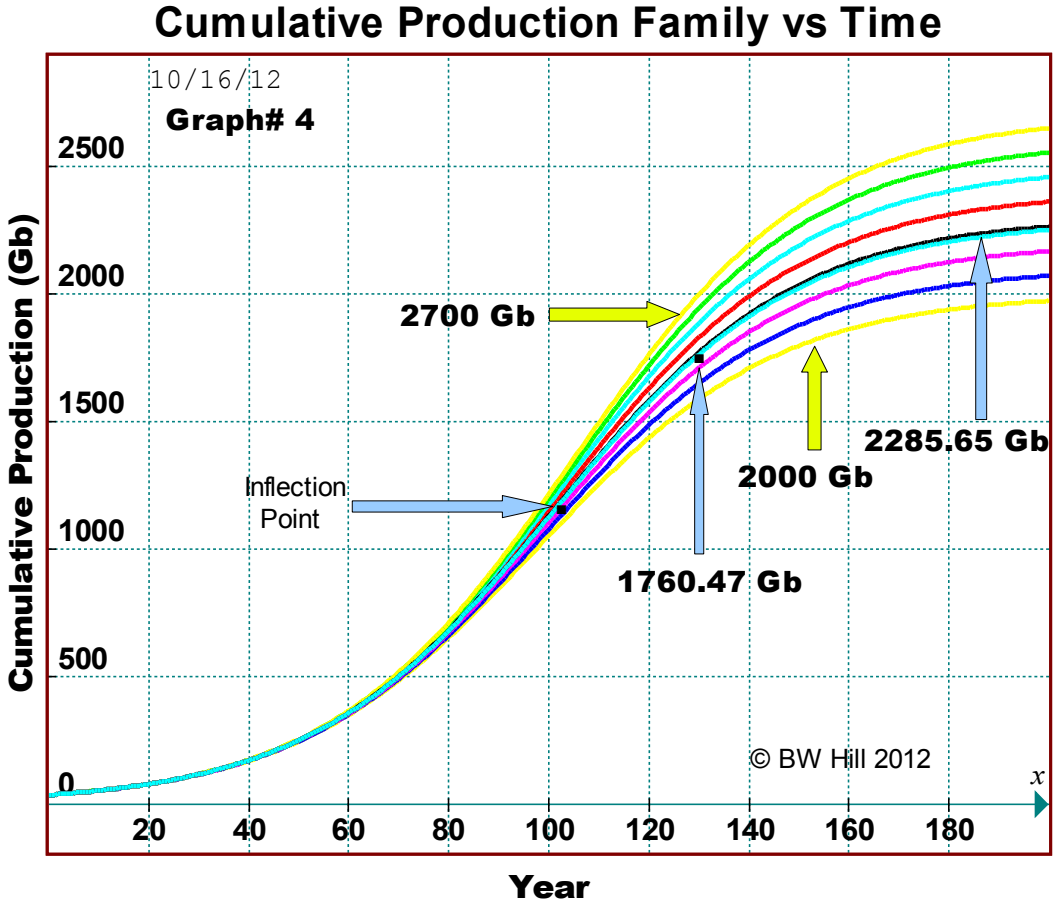


Graph# 3

The ***Hill's Group*** distrubtion is not shown for clarity of the graph; it produced r = 0.981. Eight (8) distributional forms were checked against the cumulative production data-set. The logistic distribution was the only one that produced an acceptable plot.

3.3 - Determination of P_{140} :

P_{140} is calculated using the known form of the cumulative production function (a logistic function) and the EIA[9] data-set. The EIA data-set gives 744.09 Gb produced between 1960-1999. 1999 is used as the termination date because it is prior to the rapid increase in SynCrude production (bitumen) which occurred in the early 2000's. As previously stated, the CPF is a family of curves. Shown in *Graph#4* are the curves with an abscissa (maximum production) of 2000-2700 Gb. The curves were derived from the equation of the *blue* curve, ***Hill's Group,*** in *Graph#2*.



Graph# 4

The curve which best fits the 1960-1999 EIA data of 744.09 Gb lies between the 2200 Gb curve which produces 738.17 Gb, and the 2300 Gb curve which produces 759.42 Gb for the 1960-1999 period. Interpolating; the best fit curve is generated with an abscissa of 2285.65 Gb. **P_{140}** is determined as ***2285.65*** Gb (STB) (*light blue curve below black*). The inflection point of the 2285.65 Gb curve occurred in September, 2000 at 1142.81 Gb (*Note: Graph# 4 gives cumulative production at beginning of year, the EIA data set reports year end*).

4.0 - Determination of E_{TP} :

Evaluation of E_{TP} from *Equation# 7* requires the determination of three variables: mass of the crude (m_C), mass of the water (m_W), and the temperature of the reservoir (T_R). These must be determined at time (t).

1) The mass of crude at time (t) is derived from the cumulative production function,

2) the mass of water is derived from the average % surface water cut (fw) of the reservoir,

3) temperature of the reserve is derived from the well depth. This assumes an earth temperature gradient of 1°F increase per 70 feet of depth.

1) *mass of crude:*

The cumulative crude flow at time (year) is given by its logistic function in billion barrels (Gb):

$$Gb = \frac{2285.65}{1 + 64.8708\ e^{(-0.0414*year)}}$$

Equation # 8

This is the cumulative production equation for the light *blue* curve (***2285.65*** *Gb)* in *Graph# 4*.

2) *mass of water:*

Water injection to enhance production began to be widely applied about 1930 (year 30). It is assumed that surface water cut (fw) increased as fields aged, and as the water injection method was more universally adopted. Exact data on average world surface water cut is not available, but estimates of major fields indicate it must be, as of 2012, at least 35%. This initial estimate is refined through the application of the *Buckley-Leverett Equation*[10]. This equation is a First Law statement that defines fluid flow through a porous media. It is the foundation of all modern reservoir engineering methodologies.

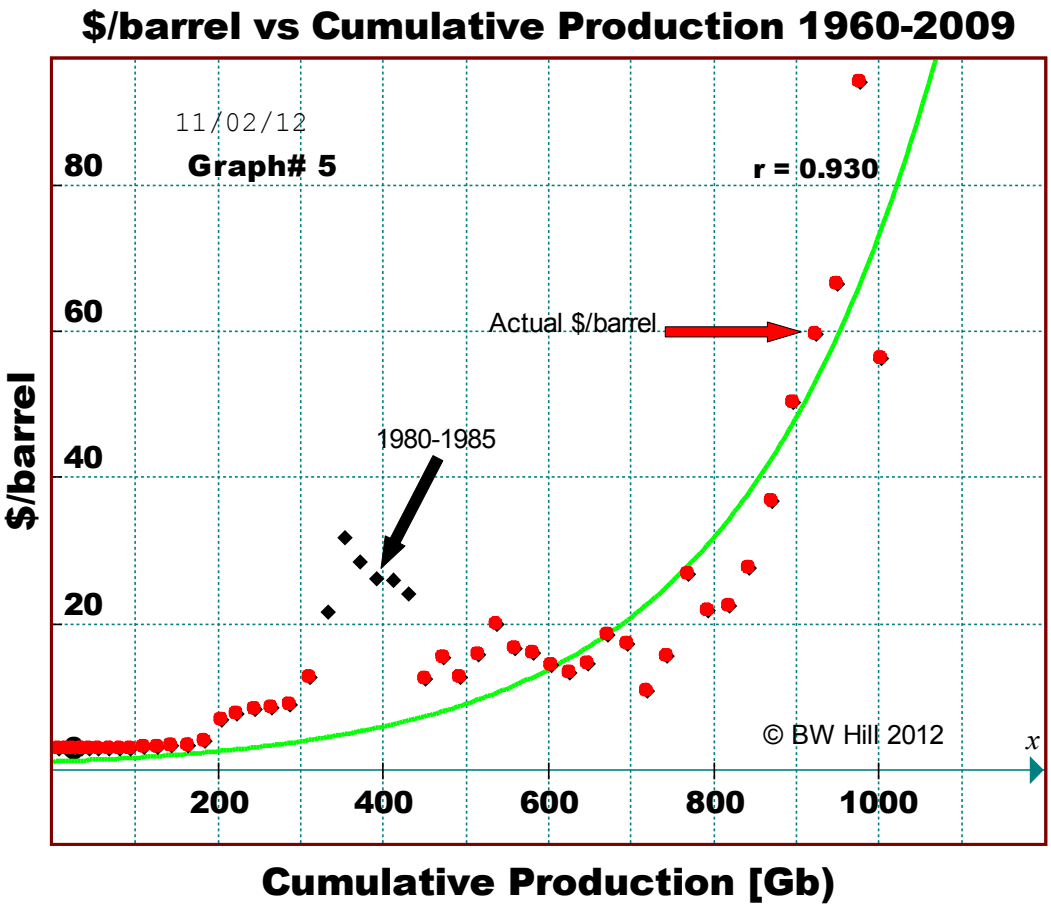
The *Buckley-Leverett Equation* can not, however be directly applied to the world's petroleum reservoir to determine surface water cut. It requires as inputs several parameters, such as the relative permeability of oil and water in the reservoir, their viscosity, porosity, OOIP (original oil in place), and others. Most of which are unknown. It also makes assumptions, such as a single layer homogeneous reservoir, which the world's reservoir is not.

The equation can, however, be used to determine the form of the surface water cut curve. The form of the water cut function, using reasonable approximations for parameters, always results in a higher order polynomial of the 5th degree. A curve is generated (*Graph# 6*) using approximate parameters, and the curve is then rotated until two criteria required by the E_{TP} function are met. Those two criteria are:

1) The E_{TP} function generated must approach E_G as N_p approaches P_{140}.
2) The $/barrel vs E_{TP} function must produce equivalent results to the $/barrel vs Cumulative Production function.

First criteria: the value for the E_{TP} function generated can not exceed $E_{G,}$ crude's specific exergy; to do so would be a violation of the *First Law* . The E_{TP} function must also be an increasing function; this is guaranteed by the *Second Law* requirement that entropy production must accompany any process. E_{TP} increases as N_p increases, and N_p is bound by $P_{140.}$ Therefore: $E_{TP} \rightarrow E_G$ as $N_P \rightarrow P_{140}$.

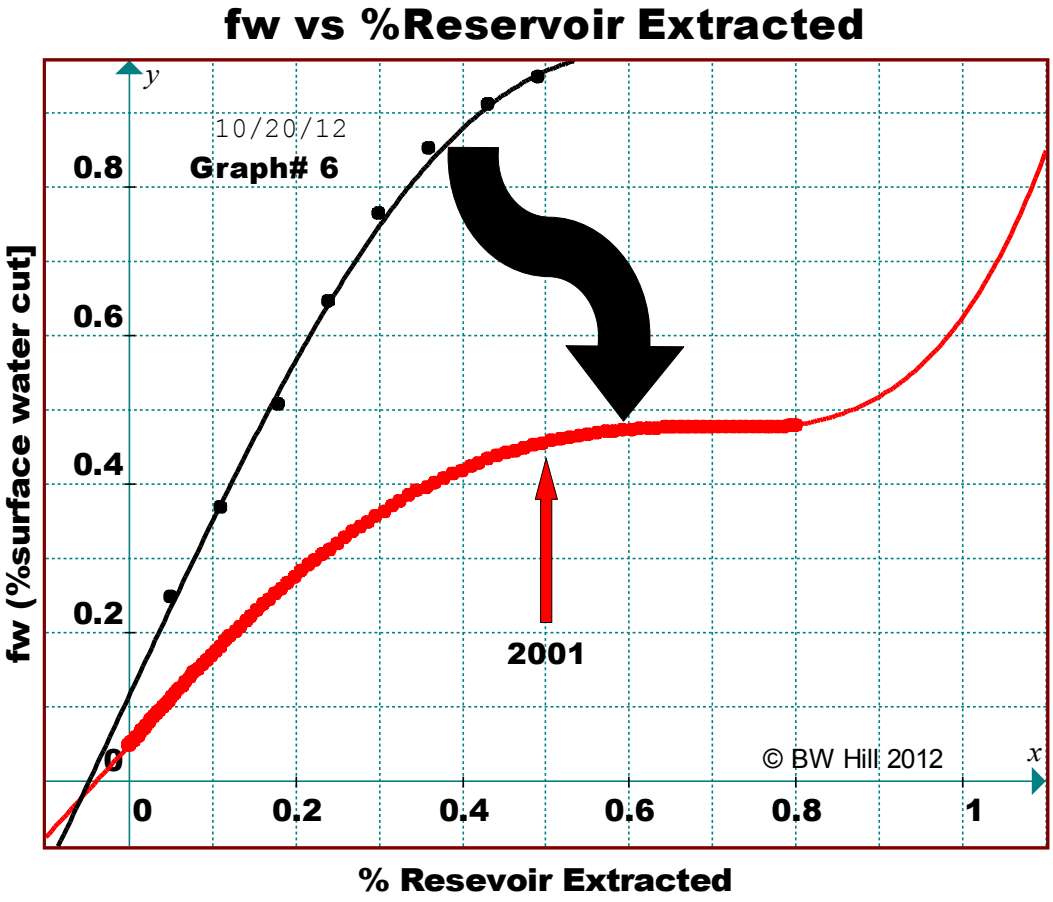
Second criteria: As N_p approaches P_{140} entropy production in the **PPS** increases the energy required to produce crude oil and its products. As cumulative production increases, the energy cost to produce it must increase. Therefore, it is to be expected that the price of crude is highly correlated to the cumulative production function. This is shown in *Graph #5* where cumulative production is zero (0) for 1960.


$/barrel vs Cumulative Production 1960-2009
11/02/12
Graph# 5
r = 0.930
Actual $/barrel
1980-1985
© BW Hill 2012
x
$/barrel
80
60
40
20
200
400
600
800
1000
Cumulative Production [Gb)

Graph# 5

The curve generated is a logistic function (r = 0.930). The six (6) black dots on *Graph# 5* represent the years 1980-1985 and are considered anomalous. They are not included in the data-set that produced the curve. There is both historic and mathematical justification for this exclusion. Between the years 1980-1985 Saudi Arabia (the world's largest producer at the time)[11] reduced their production by almost 50% to force prices higher. Other OPEC members at the time also participated in the attempt. Prices increased by 292%, and the mean price for the six years was over 3 standard deviations from the curve for this period. This price increase was a temporary artifact produced by a transitory geopolitical event which is not likely to be repeated.

The surface water cut function (fw) is shown in *Graph #6*[12,13].



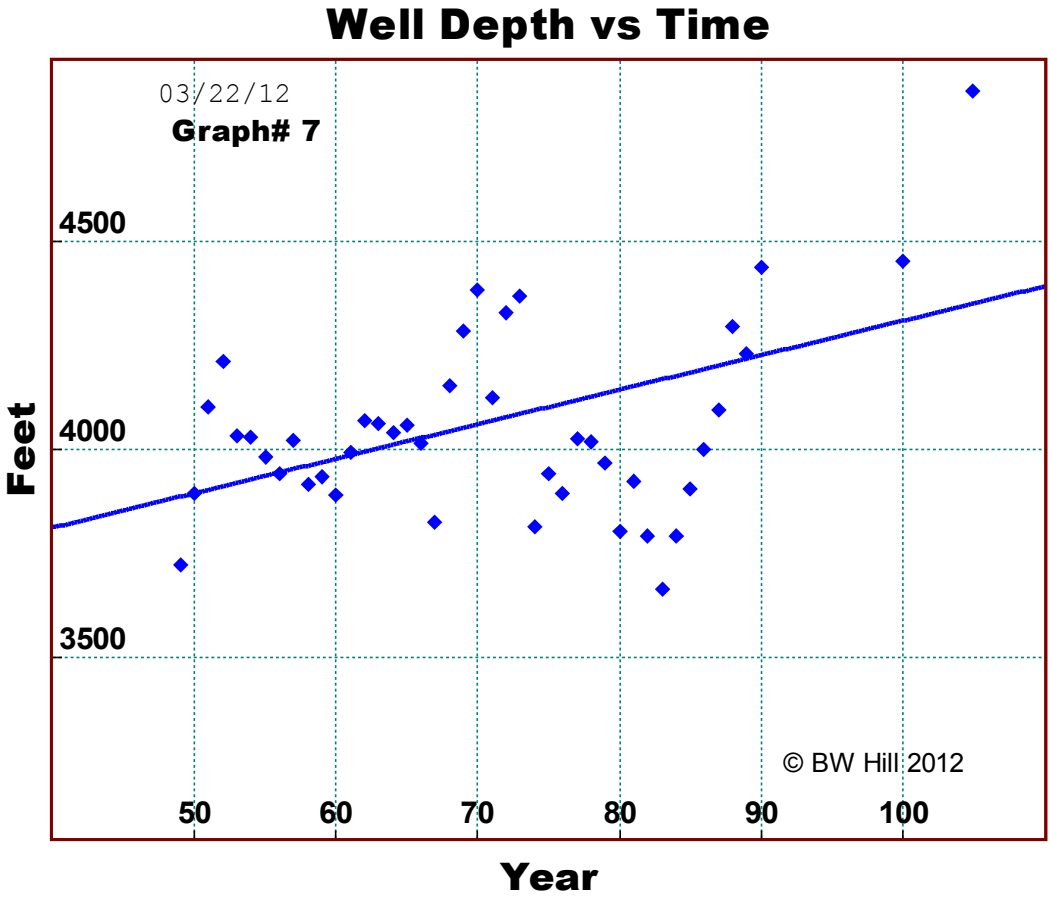
Graph# 6

The *red* curve is generated by rotating its parent, the *black* curve, until both the *First* and, *Second criteria* mentioned above are satisfied; (*see* ***4*** **-** 2 *mass of water:*). The surface water cut (fw) of the *red* curve appears to have plateaued about mid 2005 at 54% of $\mathbf{P_{140}}$. Surface water cut will not start increasing again significantly until about 80% of the $\mathbf{P_{140}}$ reservoir has been removed.

3) *temperature of the reserve:*

More than half of the oil wells ever drilled have been drilled in the United States. Because the EIA has maintained records on the depth of most of the oil wells drilled there, it is a good proxy for average world well depth. It is assumed that the life span of the average well is 20 years. Past 20 years most wells are either shut-in, or their production has fallen to a small percentage of its original amount. A twenty year moving average is used to determine average well depth at time, year = #. The temperature of the reservoir is calculated from the earth temperature gradient of 1°F per 70 feet of depth[14].

A plot of EIA well depth data is shown in G*raph# 7*[15].



Graph# 7

4.1 - Evaluating the E_{TP} function:

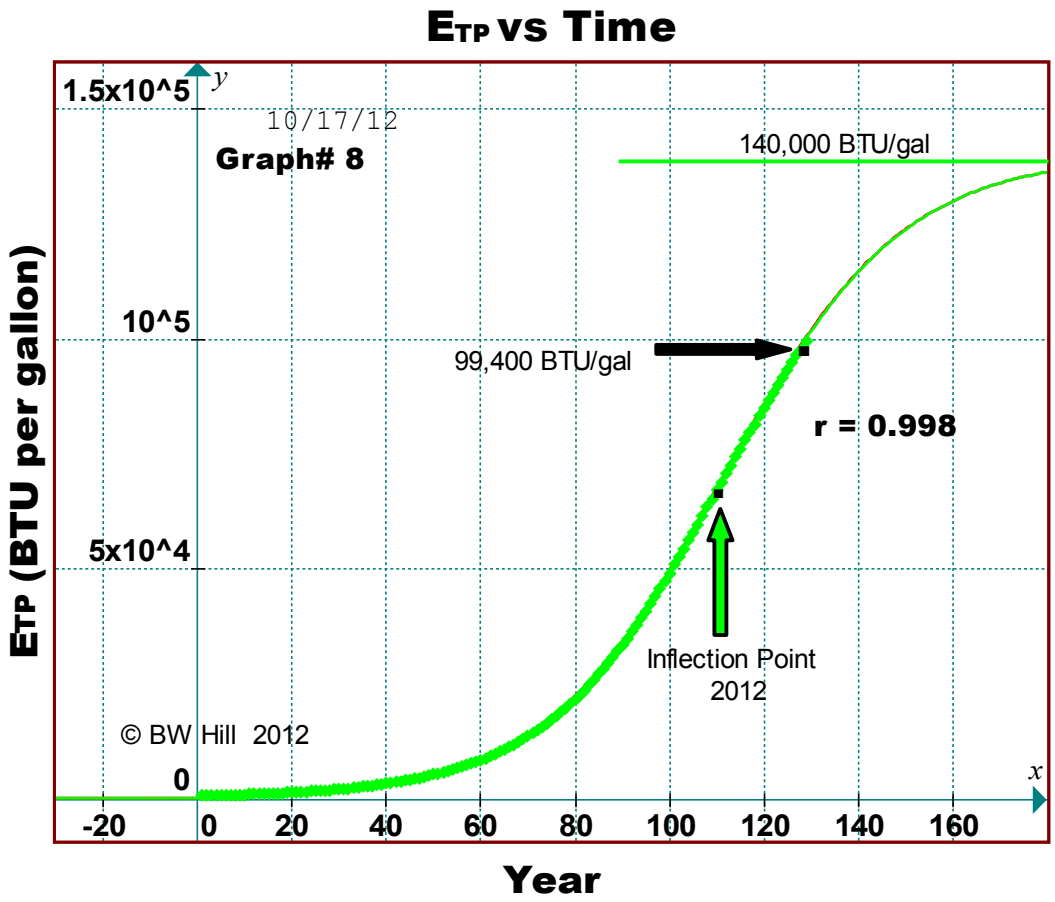
The program employed to calculate E_{TP} (*Equation #7*) is the C++ program *Etp*X, which was developed in house by the ***Hill's Group***. ***Chart# 1*** shows its output for selected years. Values given are for beginning of year.

Year	*Well Dept ft*	*Etp Inc*	∑ Etp Inc
		BTU/gal	BTU/gal
1901	3487.50	16.92	762.03
1902	3495.81	16.97	787.53
1903	3504.12	17.01	814.13
1904	3512.43	17.05	841.88
1905	3520.74	17.09	870.83
1906	3529.05	17.13	901.03
1907	3537.36	17.17	932.53
1908	3545.67	17.21	965.38
1909	3553.98	17.25	999.64
1910	3562.29	17.29	1035.37
⋮	⋮	⋮	⋮
1940	3811.59	23.47	3418.07
1941	3819.90	23.76	3576.27
1942	3828.21	24.06	3742.18
1943	3836.52	24.37	3916.18
1944	3844.83	24.70	4098.67
1945	3853.14	25.03	4290.07
1946	3861.45	25.38	4490.81
1947	3869.76	25.74	4701.36
1948	3878.07	26.11	4922.19
1949	3886.38	26.50	5153.80
1950	3894.69	26.89	5396.72
⋮	⋮	⋮	⋮
1980	4143.99	48.48	21606.53
1981	4152.30	49.59	22594.83
1982	4160.61	50.71	23621.89
1983	4168.92	51.85	24688.31
1984	4177.23	53.01	25794.58
1985	4185.54	54.18	26941.09
1986	4193.85	55.37	28128.07
1987	4202.16	56.56	29355.63
1988	4210.47	57.76	30623.71
1989	4218.78	58.96	31932.09
1990	4227.09	60.16	33280.38
⋮	⋮	⋮	⋮
2010	4393.29	78.39	66401.28
2011	4401.60	78.87	68193.51
2012	4409.91	79.31	69980.22
2013	4418.22	79.71	71759.19
2014	4426.53	80.09	73528.32
2015	4434.84	80.44	75285.64
2016	4443.15	80.77	77029.36
2017	4451.46	81.08	78757.82
2018	4459.77	81.37	80469.52
2019	4468.08	81.66	82163.11
2020	4476.39	81.94	83837.39
⋮	⋮	⋮	⋮
2027	4534.56	84.09	94945.42
2028	4542.87	84.46	96438.26
2029	4551.18	84.85	97906.70
2030	4559.49	85.27	99350.66

Chart# 1

The output of **Chart# 1** is plotted in *Graph# 8*. Like the cumulative production curve of *Graph# 2*, the E_{TP} curve of *Graph# 8* is a logistic function. The curve shown represent values generated by the program using P_{140}, and fw values from the function shown in *Graph #6* . As a result of the fixed specific exergy of petroleum, E_G (140,000 BTU/gal) E_{TP} must approach E_G, and it must approach E_G as N_p approaches P_{140}. Any other behavior would be a violation of the definition of P_{140}, or the *First Law* and *Second Law.*

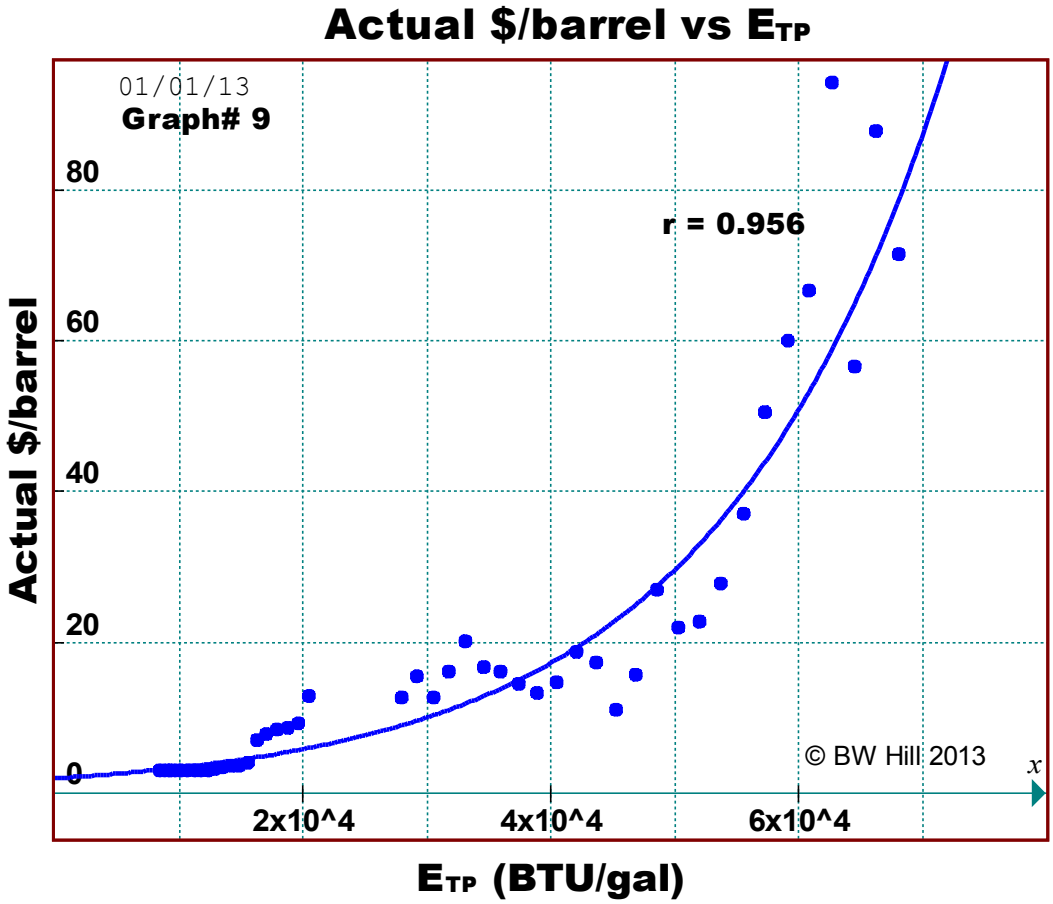
The green curve shows E_{TP} approaching the asymptotic line of 140,000 BTU/gal, satisfying the *First criteria*. The E_{TP} function will be approaching its asymptote at approximately the same time that the **CPF** of *Graph# 4* will be approaching its asymptote; at about year 2260. The inflection point occurred in June 2011, 10.7 years after the inflection point for the **CPF** occurred, r = 0.998.



Graph# 8

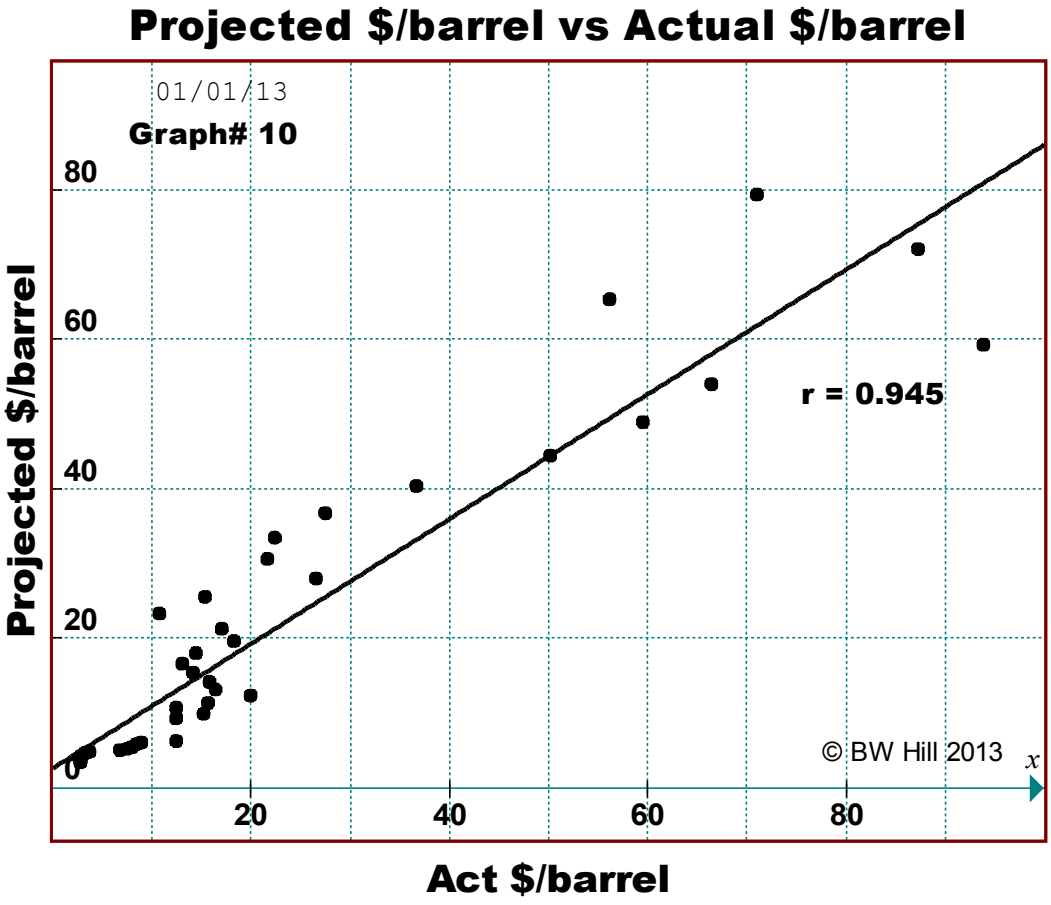
4.2 - Verification:

Graph# 9 shows the relationship between $/barrel and E_{TP}. The curve generated is an exponential function, r = 0.956. The years 1980-1985 are not included in the data-set that produced the curve (*see Graph# 5*). The blue dots represent prices reported by the EIA for WTI for the years 1960-2011.



Graph# 9

Graph# 10 shows the linear relationship between the projected $/barrel from *Graph# 9*, and the actual $/barrel from the EIA data-set, r = 0.945. The prices used are those quoted by the EIA for WTI for the years 1960 to 2011. The years 1980-1985 are not included (see *Graph# 5*). This graph demonstrates that the *Second criteria* is satisfied.



Graph# 10

4.3 - EIA Determination of CPF:

The EIA's record of cumulative world production is a critical variable in the analysis. From its creation as an agency of the Department of Energy in 1974[16], the Agency took upon themselves the monumental task of evaluating world energy production; of which petroleum is a significant portion. The Agency had reliable reports from the G7 nations, who constituted the bulk of petroleum

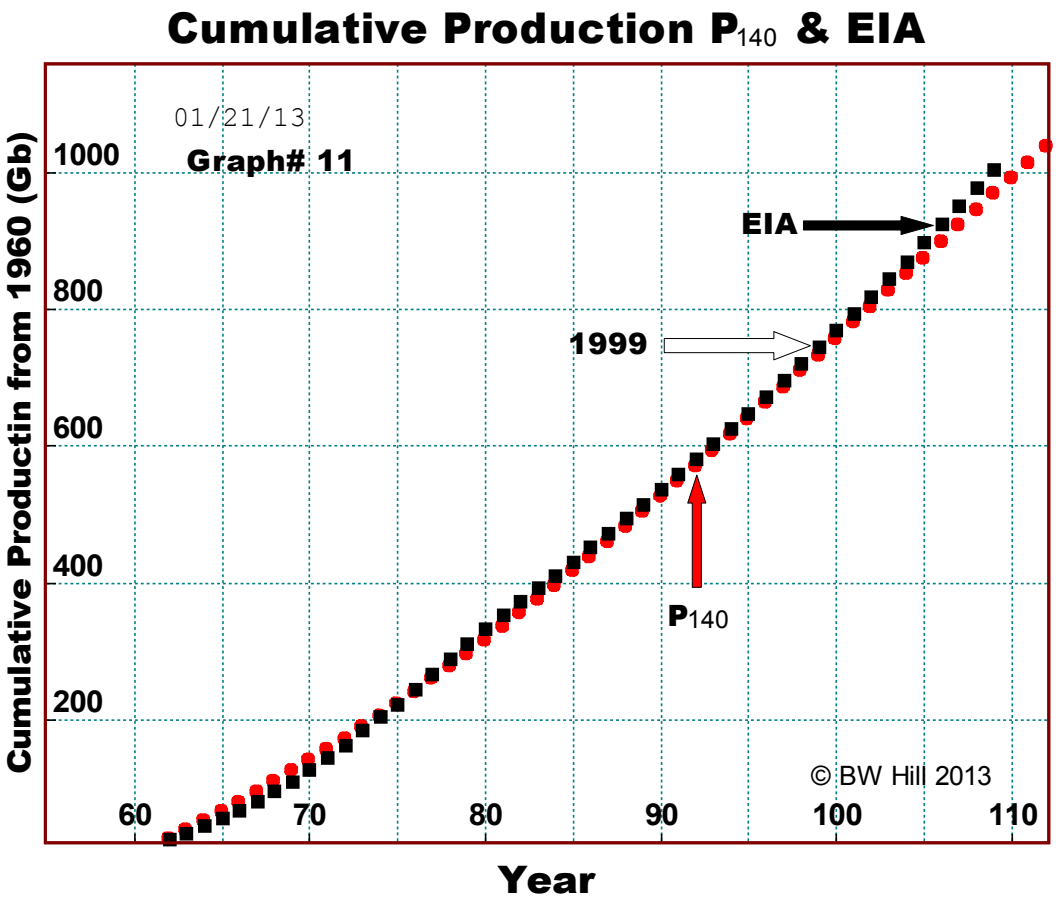
consumption at the time, but others were less forthcoming. At the time, approximately 25% of the world's petroleum production was locked behind the Iron Curtain of the Soviet Union's sphere of influence. Economic reports from Moscow where "notoriously inaccurate". The Soviet bureaucracy was evidently more interested in the propaganda benefits of their economic reports than their accuracy. With more than 40,000 fields scattered over the entire globe, and many sovereign nations regarding oil production as a critical strategic commodity, acquiring accurate data must have been daunting. The Agency had undertaken an almost insurmountable task.

To compensate for the lack of verifiable production data, the Agency looked to the most accurate data available to construct a model. Many significant production areas in the United States had been keeping records since the turn of the 20th century. *The Railroad Commission of Texas*[17], was establish in 1891. It had been given the task of monitoring the largest producing state in the union, and had kept reliable records since 1935. The model adopted by the EIA was the logistic function; this is the model that was presented to an API conference in 1956 by Marion King Hubbert.

From 1960 until 1999 the EIA followed the curve closely. The production reported by the EIA deviates from the curve ($\mathbf{P_{140}}$) for the 1960 -1999, 40 year, 744.14 Gb reported cumulative production, by *0.06 Gb*[18]. After 2000 the Agency appears to have changed their reporting methodology. From 2000 to 2005, the 128.08 Gb of their reported cumulative production deviates from the $\mathbf{P_{140}}$ curve by 4.*33 Gb!* This was during the period when the Agency began including other liquids in their production numbers. SynCrude and extra heavy were the first. It appears that the EIA may have changed their model from a logistic function to a power function, which also produces a comparatively high correlation coefficient to the production of that date. The power function, however, would indicate that production would eventually approach infinity. It is also possible that the agency became aware of a previously unidentified skewness in the production distribution (*see* **9.0 - Error Analysis:**).

The high correlation seen in *Graph# 5* between price and cumulative production results from the use of *Equation# 8* in the computation of cumulative production. It represents *conventional crude* production projected from the logistic function that was used by the EIA for forty years. The $\mathbf{E_{TP}}$ model explains the relationship between cumulative conventional crude production and price. Production of other liquids (API < 30°) require higher per unit production energy, or have lower (API > 45°) specific exergy values (see *Graph# 20*). This results in higher per unit production costs, or lower per unit energy delivery. It has been conventional crude's production energy costs that have determined the price of crude oil.

Graph# 11 shows the cumulative production from 1960 for the $\mathbf{P_{140}}$ distribution and the reported EIA data. The red dots are $\mathbf{P_{140}}$; **black** squares are EIA. The two distributions began diverging about the year 1999 (year 99 on the graph).



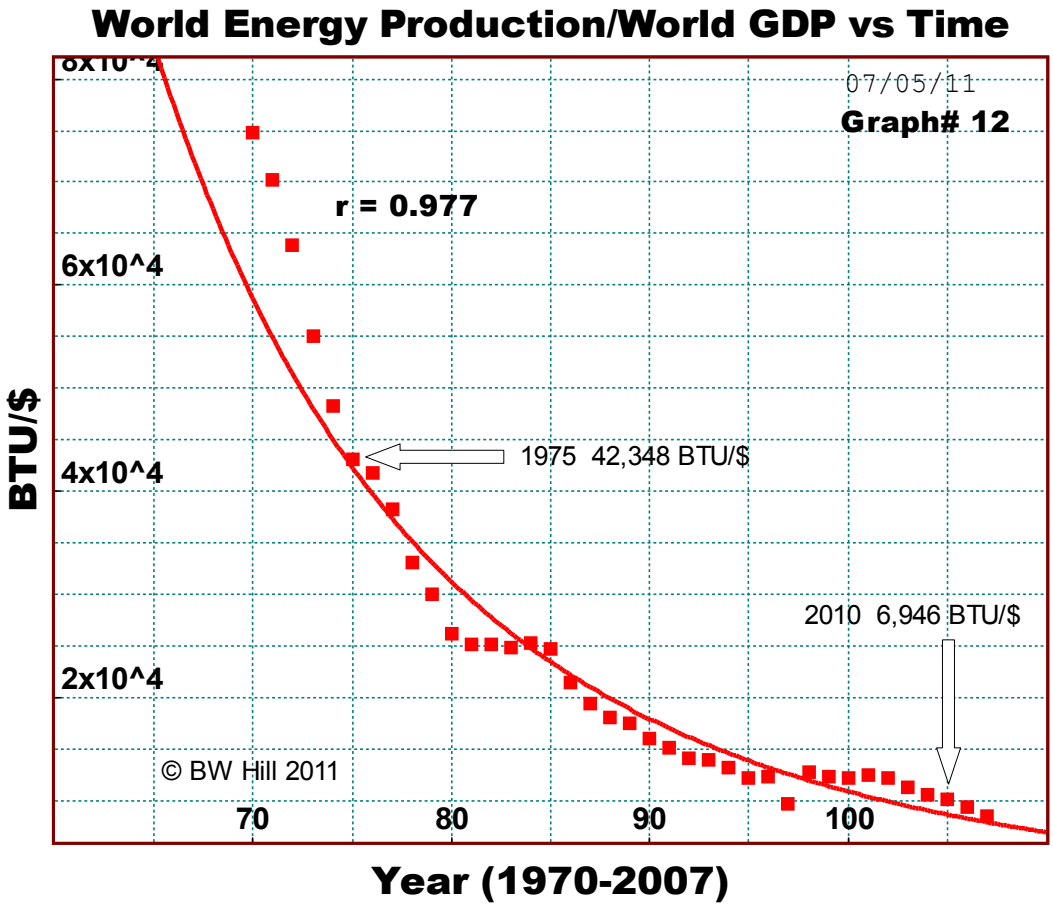
Graph# 11

5.0 - Work input at the Well Head, E_p:

Work, E_p, must be invested at the well head to extract petroleum. Energy flows from the well head to the **PPS** where it is converted into the work used at the well head to extract the petroleum. The goods and services used in the extraction process are determined by the quantity of work invested. Energy and work, though measured with the same units, such as BTU, are differentiated because energy is a fundamental property, while work is the result of a process (work is not a property). The conversion of energy into work always results in losses (*Second Law*).

The thermal efficiency with which energy is converted into work is symbolized by the Greek letter eta, η. Its calculation is given by *Equation# 6*. To calculate η, which also equals $E_p \setminus E_{TP}$, it is necessary to determine E_p. Since there is no *Second Law* statement that can that can be employed, as in the determination of E_{TP}, it is necessary to derive E_p and η empirically.

To evaluate $\mathbf{E_p}$ a BTU/$ costing system is employed. A BTU is a static quantity; it does not change with position or time. Dollars, however, are constantly changing so any metric which includes them must be defined in time. *Graph# 12* is derived from data taken from the *World Bank*[19] and the *EIA*. The *World Bank* provides world GDP in trillions of dollars (10^{12}) for the years 1970-2007. The EIA[20] provides total world energy production in quadtrillion (10^{15}) BTU. Dividing gives BTU/$ for the given years.

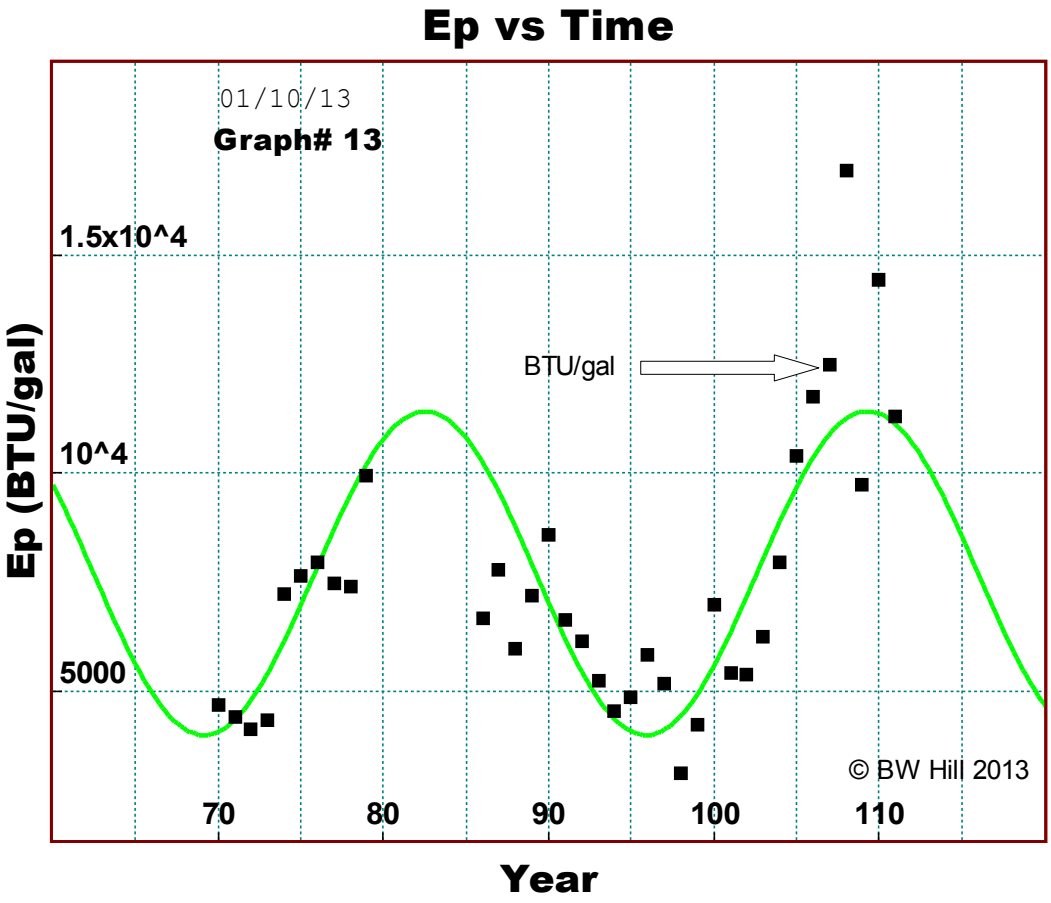


Graph# 12

Graph# 12 gives the average number of BTU that could be purchased for one dollar during a given year. It also indicates the number of BTU that were on average required to generate a dollar's worth of goods and services for any given year[21]. The curve is a power function (r = 0.977).

To calculate $\mathbf{E_p}$ we assume that the petroleum industry pays the average world price for energy, which is what is given by *Graph# 12* for the 1970-2007 time period. The energy costs to extract a gallon of petroleum is determined by using $/barrel from the EIA 1970-2007 WTI price data-set divided by 42, giving $/gal. The work to extract a gallon of petroleum, $\mathbf{E_{p,}}$ is BTU/gal = BTU/$ * $/gal.

Graph# 13 shows the output generated for the years 1970-2007 for $\mathbf{E_p}$. Because the determination is based on the price of crude oil the sinuoidal character of the function reflects the periodicity of petroleum prices. The period of this function is 26.8 years. The years 1980-1985 are excluded from the data-set that produced the graph (r = 0.827).



Graph# 13

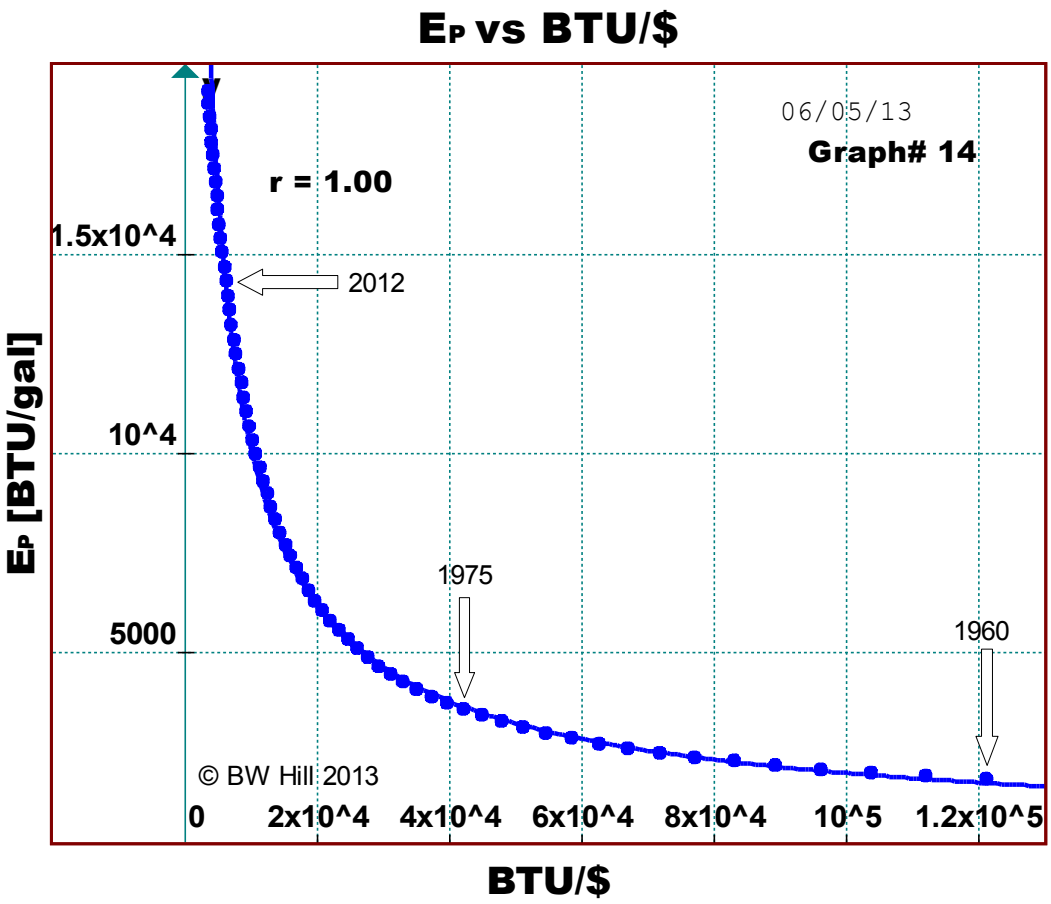
The thermal efficiency $\boldsymbol{\eta}$ is derived by calculating $\mathbf{E_p} \setminus \mathbf{E_{tp}}$ for the years 1970-2007, and then taking their average. The 38 year average for $\boldsymbol{\eta}$, using the BTU/$ approach, is determined as 0.225. This initial value of $\boldsymbol{\eta}$, derived from the BTU/$ method, is used as a check, and is refined further to generate the value of $\boldsymbol{\eta}$, and construct an **ERoEI** function.

As $\mathbf{E_P} = f(\mathbf{E_{TP}})$ it follows that $\mathbf{E_P} = \mathbf{E_{TP}} * \boldsymbol{\eta}$. This relationship is embeded in the program *E*ta$*X* that was written in house by the ***Hill's Group.*** The program steps through $\boldsymbol{\eta}$ in 0.00005 unit increments

between η = 0.15 and η = 0.30 until it finds the best $/barrel match for the 1960-2009 average. η is determined as ***0.2045*** by the program.

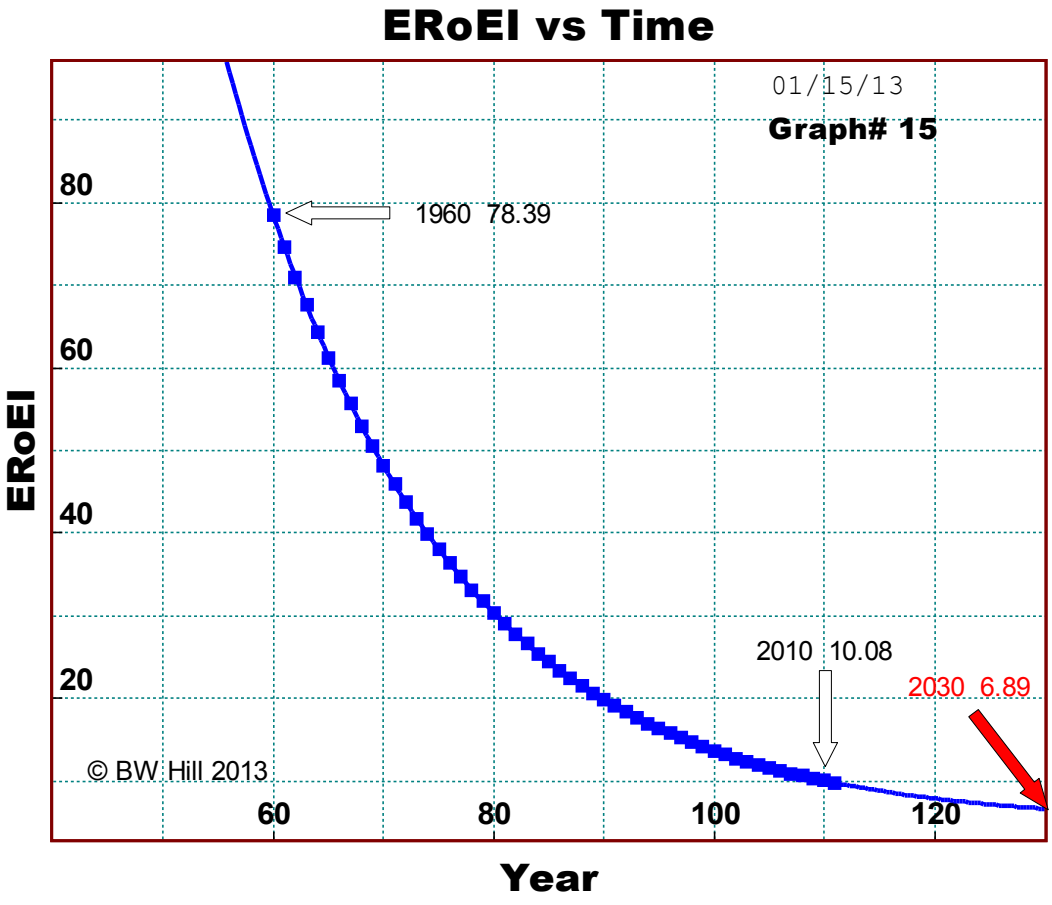
The derived value for η is reasonable as it agrees closely with the BTU/$ method, and is approximately equal to the reported efficiency of most **i**nternal **c**ombustion **e**ngines. As ICE constitute the major use of petroleum products it can be concluded that the efficiency of crude oil production would be similar.

Graph# 14 demonstrates that average world energy costs (BTU/$) and petroleum energy costs have followed the curve generated by the E_{TP} model; $E_P = E_{TP} * \eta$. As η is a constant (0.2045) it acts as a scaling parameter for the function. The curve is a power function, r = 1.00.



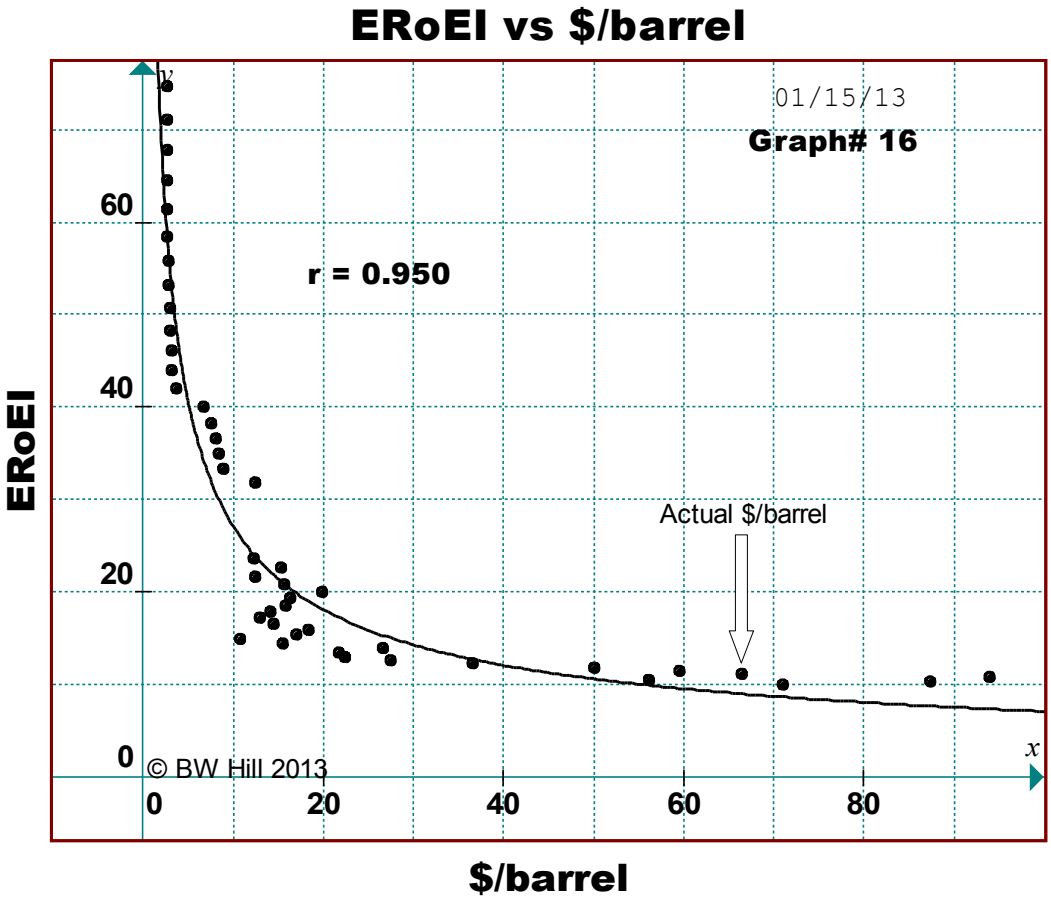
Graph#14

The **ERoEI** function generated, where **ERoEI** = $\mathbf{E_G/E_P}$ (*Equation# 4*) is shown in *Graph# 15*. The curve produced is an inverse logistic function, r = 1.00 .



Graph# 15

The relationship between $/barrel and **ERoEI** is shown in *Graph# 16*. The time period covered is between 1960-2011 for WTI. The years 1980-1985 are excluded. The graph is a power function, r = 0.950.

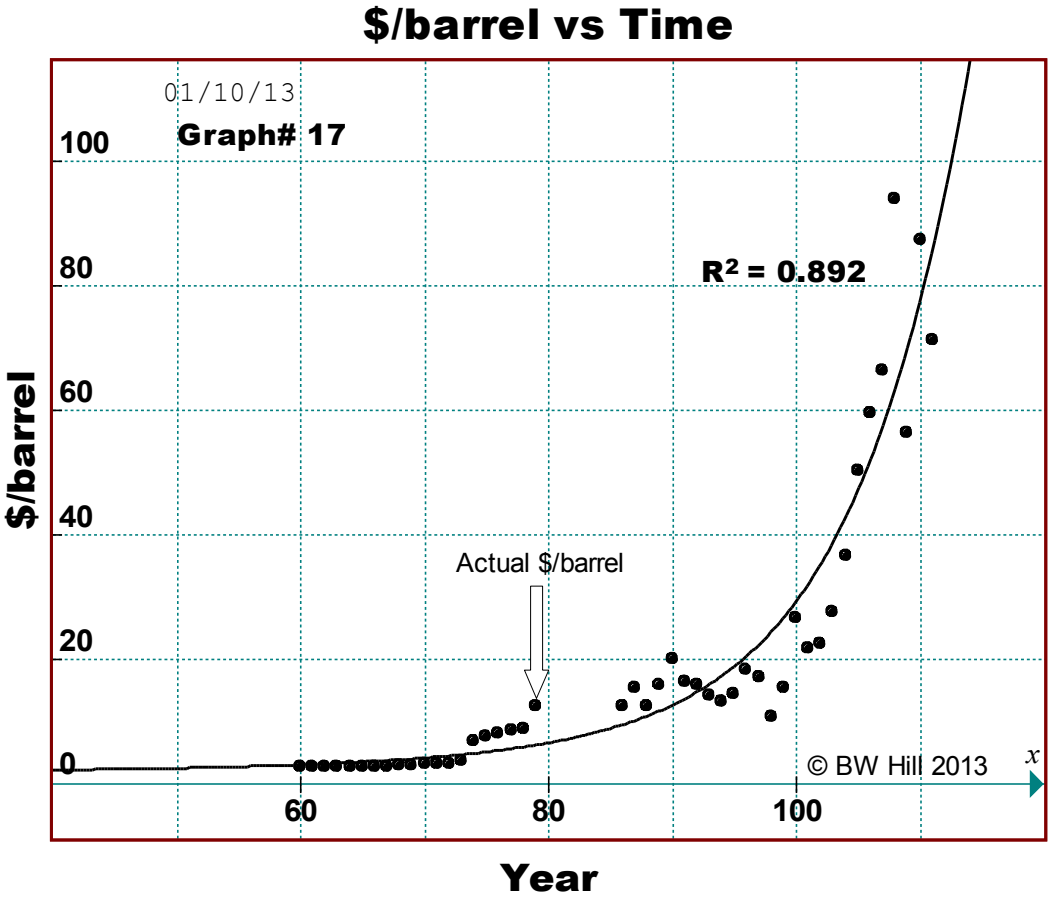


Graph# 16

6.0 - Petroleum Prices:

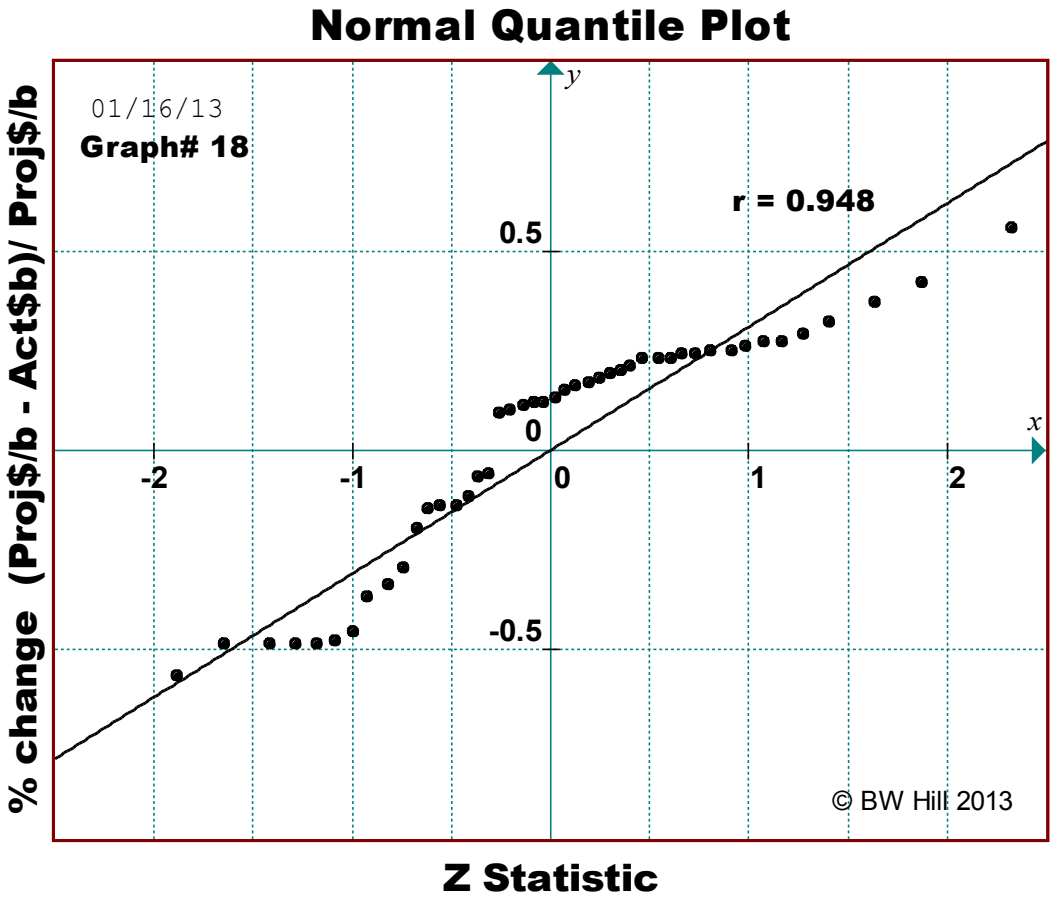
One of the most critical questions facing the investor/planner today is what changes can be expected from petroleum prices in the future. A projection derived from the $\mathbf{E_{TP}}$ model is shown in *Graph# 17.*

Graph# 17 (*black curve*) is the parametrization of the *Graph# 9* equation. It is produced by the substitution of the *Graph# 8* function for x into the *Graph# 9* equation. The black dots represent actual $/barrel as reported by the EIA for WTI for the years 1960-2011. The years 1980-1985 are not included in the data-set that produced the graph. The coefficient of multiple determination, R^2, which gives the relationship between the graph equation and the actual $/barrel = 0.892



Graph#17

The price of crude oil is not a normal distribution, but the difference between the projected $/barrel generated from the curve of *Graph# 17*, and the actual $/barrel is a good approximation to a normal distribution. The quantile plot of *Graph# 18* shows this relationship, r = 0.948.

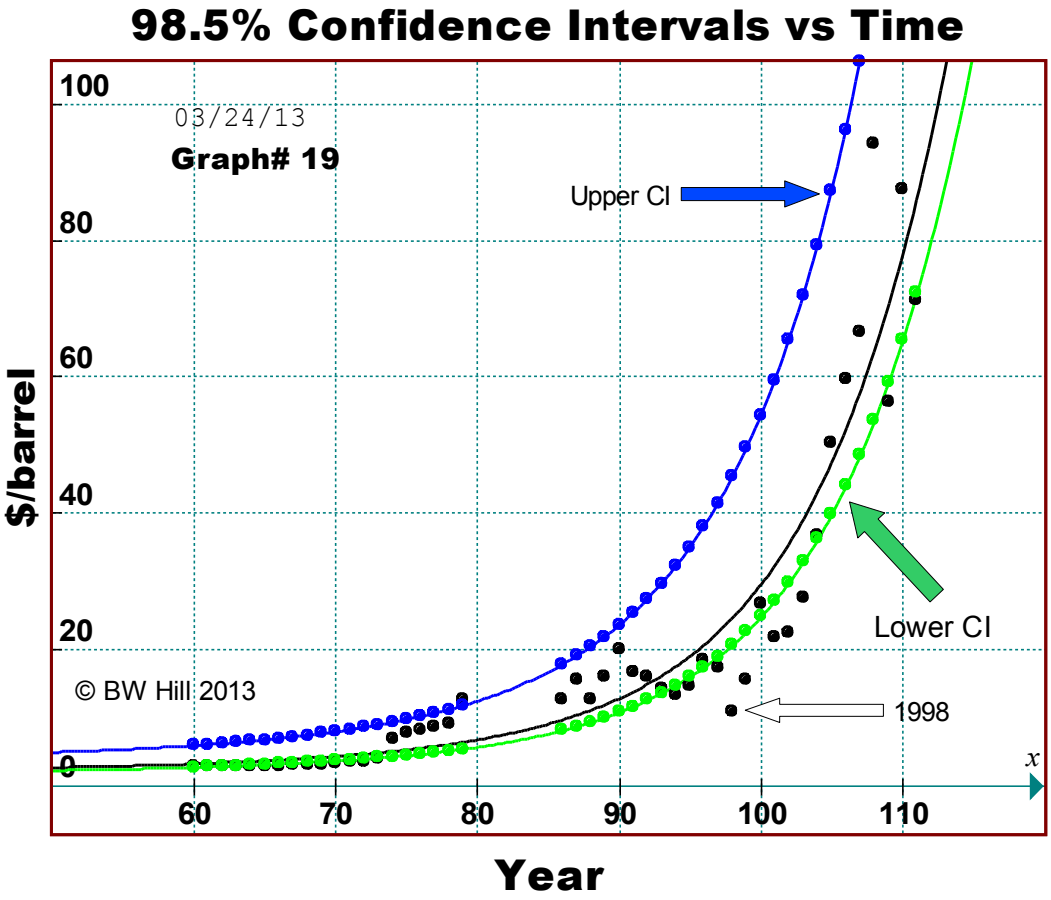


Graph# 18

Graph# 19 shows the construction of confidence intervals using the normal distribution of deviations of (Projected $/barrel - Actual $/barrel) / Projected $/barrel; *Graph# 18*. The 98.5% confidence intervals are the largest which can be used, and still be statistically significant for the given sample size. The points that fall below the lower CI result from random chance, and the unaccounted skewness of the 2285.65 Gb function of *Graph# 4*.

Although the long term movement of oil prices is well predicted by the $\mathbf{E_{TP}}$ model, its short term pricing is affected significantly by economic and geopolitical events. 1998 was the DotCom bust, 2001 the World Trade Center disaster, and 2008 the announcement by the Federal Reserve to begin large scale monetization. For each event the price of oil reacted dramatically, but eventually passed back through the curve. The mean of the percent deviation ($Projected - $Actual)/$Projected is *0.000*, stdv = 0.330. From 1960-2009 movement beyond the curve was exactly compensated for by later movement in the opposite direction. For forty four (44) years crude oil prices have, *on average*, exactly followed the curve. Although, it should be noted that the series of events that took place after 1998 kept

oil prices suppressed for seven years even though its pricing was in an upward phase, as shown in *Graph# 13*.



Graph# 19

6.1 - Affordability:

Only petroleum that is affordable to the end consumer has value as a commodity. Most of the world's petroleum resource falls outside of this affordability range. This affordable range of liquid hydrocarbons is referred to as crude oil. Crude oil is the subclass of liquid hydrocarbons that can produce more energy than is required to extract, process, and distribute it. It constitutes approximately 40% of all liquid hydrocarbon found in the earth's crust. It is the only subclass of liquid hydrocarbons that produces a value that is greater than what is required to produce it. This results from its very high initial entropic state. As entropy is transferred out of the well with its associated mass flow the entropy of the well falls, and the entropy of the environment increases. When the two are in equilibrium the well has hit the dead state.

To determine the affordability range it is first observed that *the price of a unit of petroleum can not exceed the value of the economic activity that the energy it supplies to the end consumer can generate*. To exceed that value would imply that the value of petroleum to the economy would have a neutral effect; its use would not increase GDP by more than its cost. This analytical technique does not negate the economic premise of supply and demand, it supersedes it. Producers must receive a price that is at least equal to its cost of production, and consumers can pay no more than the value of the economic activity that it can generate. When production costs exceed what the end consumer can afford to pay; production is curtailed, and eventually ceases.

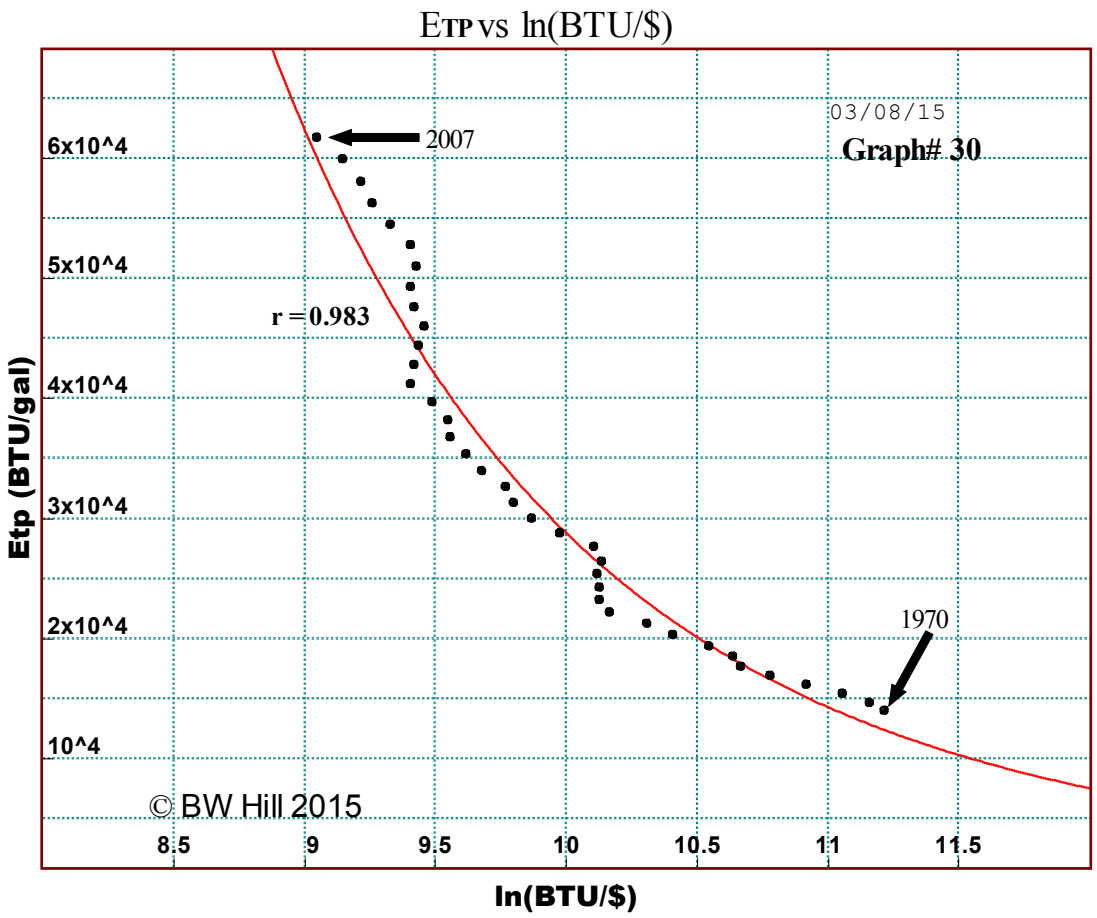
To determine the maximum affordable price to the end consumer it is necessary to derive two values:

1) the useable energy delivered per unit,

2) the dollar value of the goods and services that energy can generate.

Energy is a commodity with a monetary value, and that value is determined by market forces. Graph# 12 gives the historic dollar value of energy in BTU/$. The useable energy delivered to the end consumer is derived from the E_{TP} Model. To use dollars as a metric in the computation of affordability it is first necessary to show that a relationship exists between the energy values generated by the E_{TP} model, and and the BTU/$ function. That is demonstrated in Graph# 30:

Graph# 30 is generated by the best fit curve of E_{TP} vs ln(BTU/$). It is a power function with a correlation coefficient of r=0.983. It demonstrates that as the energy to produce petroleum, and its products increases, BTU/$ value declines. Because the BTU/$ function is the mean of all energy sources used between the years 1970 and 2007, petroleum has followed that mean closely. It indicates that the gross energy contribution of all sources has an equal impact on the economy. It is the characteristics of the the specific source that determines how, and if it is used.



As the value of the usable energy delivered from a unit of petroleum changes the price that the end consumer can pay for that unit changes. This is demonstrated in Graph# 31 by the black dots labeled 29%, and light magenta dots labeled 38%. The light magenta dots represent the **Maximum Affordability Consumer Price**, and were developed from the **ETP** model. It represents the maximum price that the end consumer can pay for petroleum. It is based on the observation that *the the energy delivered by a unit of petroleum must be capable of powering economic activity with a value equal to its price*.

The two **Maximum affordable price** curves labeled 29% (black), and 38% (light magenta) are skewed logistic curves. There is no explicit mathematical equation to describe them. They are derived numerically, and the dots represent values for specific years. The 29% curve represents the maximum theoretical energy that can be extracted from a unit of 37.5° API crude. Its value is derived from the combustion equations of hydrocarbons. The 38% curve is the average energy extracted from a hydrocarbon by the end user. **29% and 38% represent the minimum amount of waste heat that must be generated for each process to go forward.** The 38% curve passes through the **ETP** derived price curve at the inflection point of the **ETP** curve in year 2012. 2012 was the energy half way point

for petroleum production (see section **7.0**). It was the year when it required one half of the energy content of petroleum to produce the petroleum, and its products.

The individual points of Graph# 31 for the 38% curve are generated from the equation:

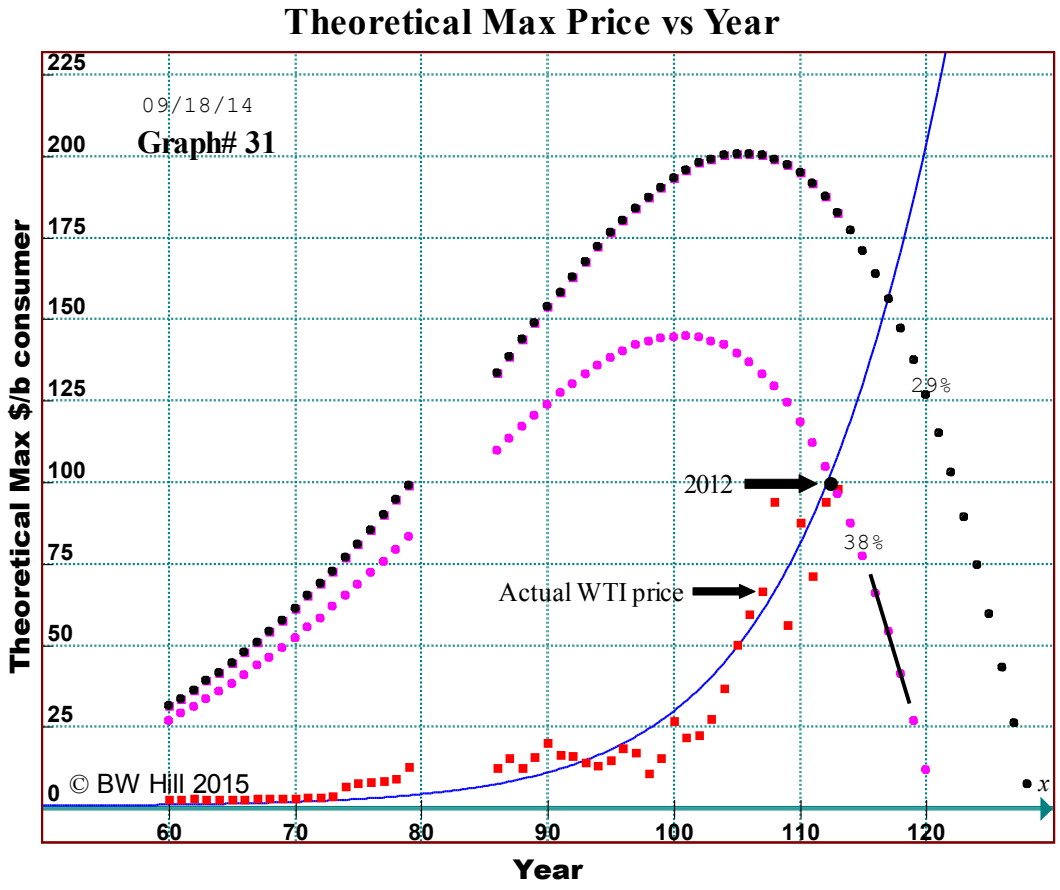
$Value per barrel = (Energy delivered - **ETP** value)/ BTU/$.

Energy delivered/ barrel = 140,000 BTU/gal x 0.62 x 42*

ETP value is derived from the **ETP** graph *42 gal/barrel

BTU/$ is taken from the **BTU/$** function of Graph# 12

*140,000 BTU/gal - the energy content of 37.5° API crude



Graph# 31 indicates that crude oil reached its maximum sustainable price in 2012 at $104.58 per barrel. That is were the maximum affordability curve crosses the production cost curve. Furthermore, it indicates that the price of petroleum after 2012 will begin a long term price decline, and that this will be occurring even as the cost of producing petroleum continues to increase.

7.0 - Points of Criticality:

Chart# 1 highlights two years, 2012 and 2030. The E_{TP} model indicates that these are *Points of Criticality* for world petroleum production.

1- 2012) Output from the E_{TP} fuction, *Graph# 8*, indicates that 2012 is the year that E_{TP} crosses the 70,000 BTU/gal point. It is the specific energy half way point for world petroleum production. *Beyond this point the world's petroleum producers can no longer increase production by directly utilizing only oil's own specific exergy,* E_G (energy from petroleum could only be made available by cannibalizing the embedded energy in existing infrastructure). This can be demonstrated

through a simple arithmetic progression. It also indicates that E_D (*Equation# 5*), the specific energy per gallon delivered to the end consumer, has also passed through the half way point; as $E_D = E_G - E_{TP}$. Total E_D (E_D * **Yearly Production**) can only be increased by increasing production faster than its per unit decline reduces it. Production, however, can no longer be increased because the energy would no longer be available to perform the task. Because all economic activity requires energy to be performed, demand for petroleum products will begin to fall in conjunction with increasing price. 2012 is the point where the petroleum production system (**PPS)** becomes a larger user of the energy that comes from crude oil than is the non-energy goods producing sector (**NEGs**) of the economy.

2 - 2030) 2030 will be the year that a discontinuity appears on the P_{140} curve. It is when the average barrel of crude will have reached the "dead state". After that date petroleum will no longer act as a primary energy source. This determination is derived from the calculation of the maximum attainable Second Law Efficiency (SLE) for 35.7° API crude. The SLE gives the maximum theoretical work that can be extracted from a fuel, and the minimum energy that must be given up as waste heat for the process to go forward. It is computed by Exergy analysis using the combustion equation of the hyrocarbon in question. **Chart# 2** below shows the SLE for various hydrocarbons: Exergy is given in BTU/gal.

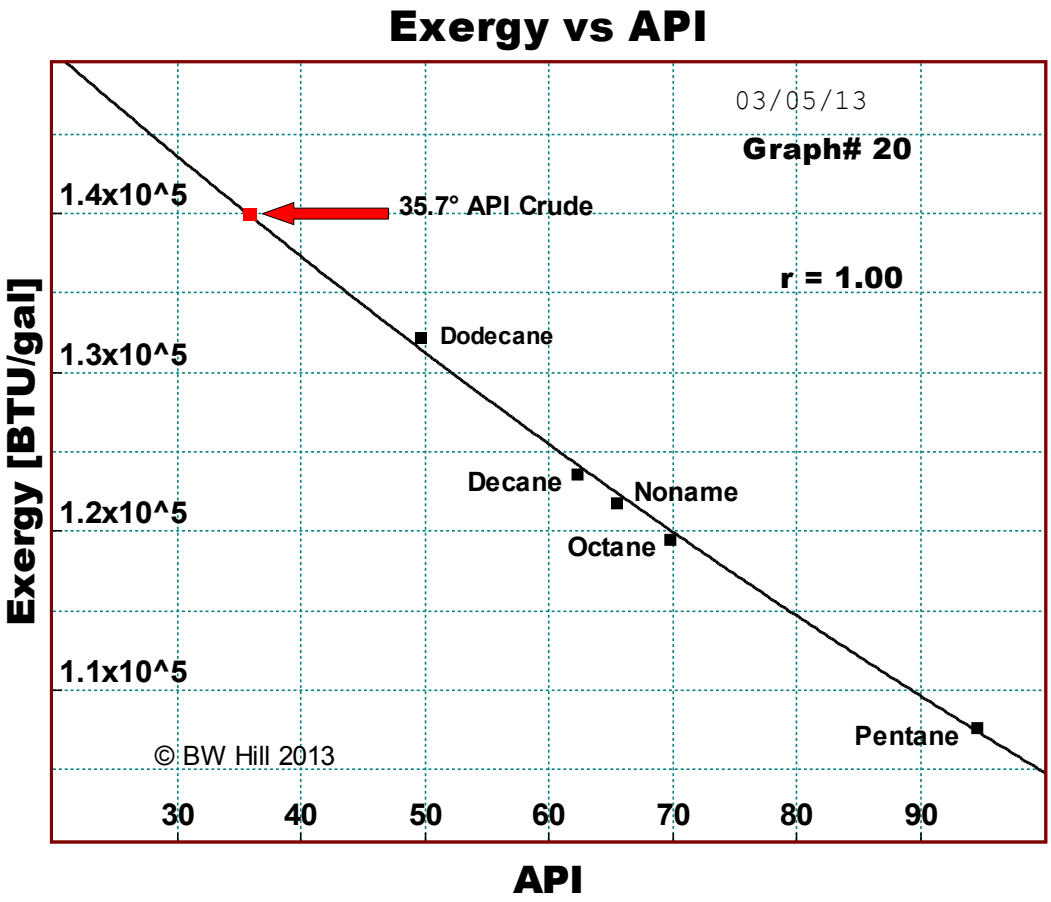
Name	Formula	API	SLE	Exergy
Pentane	C_5H_{12}	94.54	0.571	107,559
Octane	C_8H_{18}	69.78	0.702	119,436
Nonane	C_9H_{20}	65.58	0.702	121,710
Decane	$C_{10}H_{22}$	62.34	0.702	123,541
Dodecane	$C_{12}H_{26}$	49.72	0.708	132,162

Chart# 2

Hydrocarbons below Heptane (C_7H_{16}), like Pentane, have negative Gibbs energy of formation factors[22], thus lower SLE's. Because crude is composed of several hundred fractions of hydrocarbons it has no explicit formula, so there is no definitive combustion equation for it. **Chart# 2** indicates, however, that for hydrocarbons with a molecular weight greater than Heptane there is a slight increase in the SLE for hydrocarbons with decreasing API. For a 35.7° API crude an SLE of 0.71 appears reasonable.

The Exergy (E_G^{CH}) is denoted as the chemical exergy of a petroleum fraction. It is the maximum

amount of work that can be obtained from the combustion of a hydrocarbon. All references in this study to exergy refer to this quantity. For a 35.7° API hydrocarbon it is 140,000 BTU/gal. This is derived from the *Exergy vs API* graph, *Graph# 20.* 35.7° API crude closely approximates the EIA's determination from their 101.16 Gb, 2000 - 2004 reported production ; mean = 140,075 BTU/gal; stdv. = 273 BTU/gal. *Graph# 20* is an exponential function, r = 1.00.



Graph# 20

For a 35.7° API crude with an SLE of 0.71 the maximum theoretical extractable work is 99,400 BTU/gal (140,000 BTU/gal * 0.71). This point is shown on the E_{TP} *vs Time* graph, *Graph# 8*. It is also shown on *Graph# 4* as 1760.47 Gb; the point where the average barrel has reached the "dead state". The "dead state" is represented by the 6.89:1 point of *Graph# 15*.

The 6.89:1 ERoEI point represents the time at which no work can be extracted from the production of about one-half of the world's fields. This assumes that the distribution of the **ERoEI**s of the world's 48,000[23] fields lays equally about its mean. If the rate of new fields coming on line does not exceed older fields that are falling below the 6.89 point, production will decease accordingly. According to

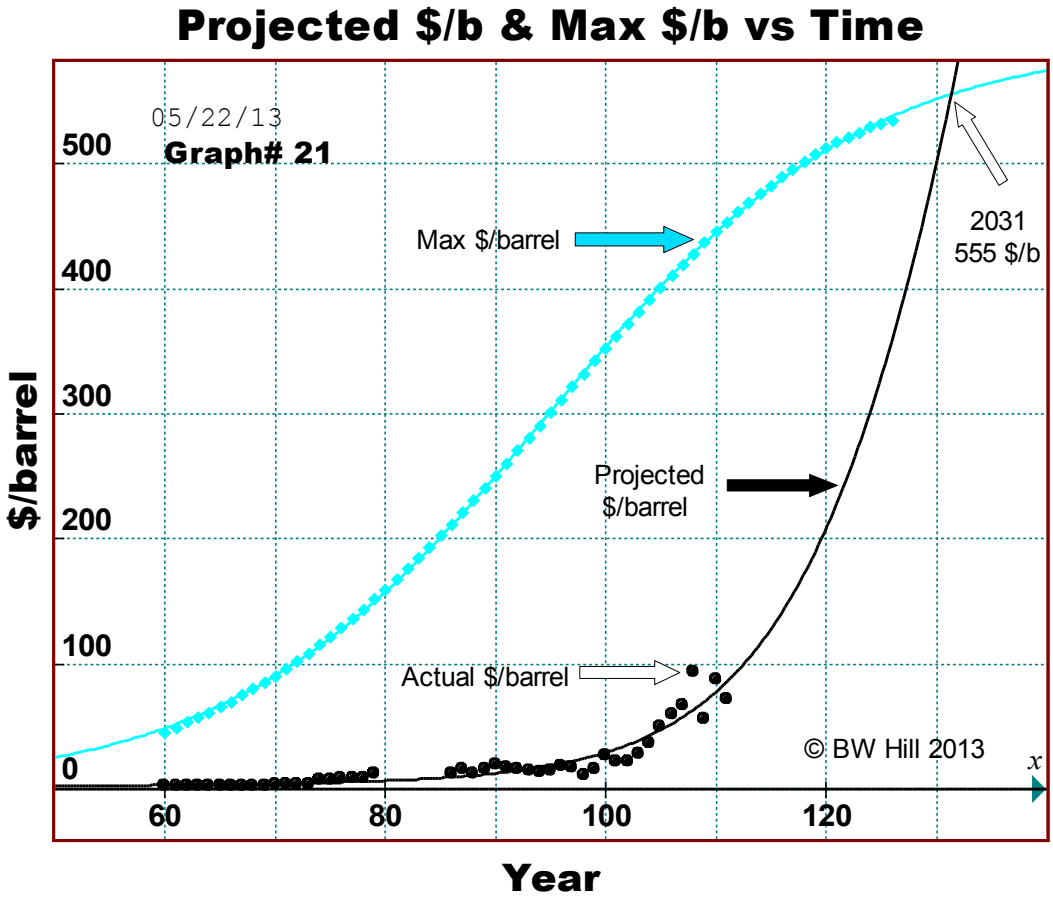
EWG's 2007[24] assessment, that will be about 12 Gb/year by 2030 (32.88 Mb/d).

As a rule of thumb, reservoir engineers use a **WOR**[25,26] (water, oil ratio) of 40:1 to determine the economic life span of a field. 40:1 is where the water cut has increased to a level that a field is no longer considered economically viable, and is shut-in. This can vary depending on the current market price of petroleum. By using *Equation# 7*, and multiplying both sides by Gb to eliminate it, as $\mathbf{E_p = E_{TP} * \eta}$, $\mathbf{E_p}$ can be calculated directly (well depth is taken as 4,000 feet). For a **WOR** of 40:1, $\mathbf{E_p}$ = 19,943.78 BTU/gal.

As **ERoEI** = $\mathbf{E_G/E_P}$ (*Equation# 4*) a **WOR** of 40:1 generates an **ERoEI** of 7.02:1 (140,000/19,943.78). This is a value close to the "dead state" value that was calculated above to be at 6.89:1. The value of the "dead state" for $\mathbf{E_{TP}}$ can also be computed from the relationship $\mathbf{E_{TP} = E_P / \eta}$, giving 97,524.60 BTU/gal for a **WOR** of 40:1. It is reasonable to assume that wells are shut-in just prior to their hitting the "dead state". The "dead state" is shown in *Graph# 8* as 99,400 BTU/gal. The close similarity (± 1.9%) between the calculated values, and practical field experience offers strong support for the validity and accuracy of the distribution of $\mathbf{P_{140}}$ and the $\mathbf{E_{TP}}$ model.

Graph# 21 shows the intersection of two curves. The blue curve gives the maximum $/barrel that can be paid by the end consumer, and the projected $/barrel price curve, *Graph# 17*. The maximum $/barrel (blue curve) is generated by dividing the computed value of $\mathbf{E_D}$ for each year from 1960 - 2026 by BTU/$ from *Graph# 12*. It is a logistic curve (r = 1.00). $\mathbf{E_D}$ gives the energy delivered to the average end consumer from a gallon of crude oil. $\mathbf{E_D}$/BTU/$ gives the dollar equivalent value of a gallon of crude delivered to the end consumer for a specfic year. For petroleum to remain an economically viable commodity, its price can not exceed this value.

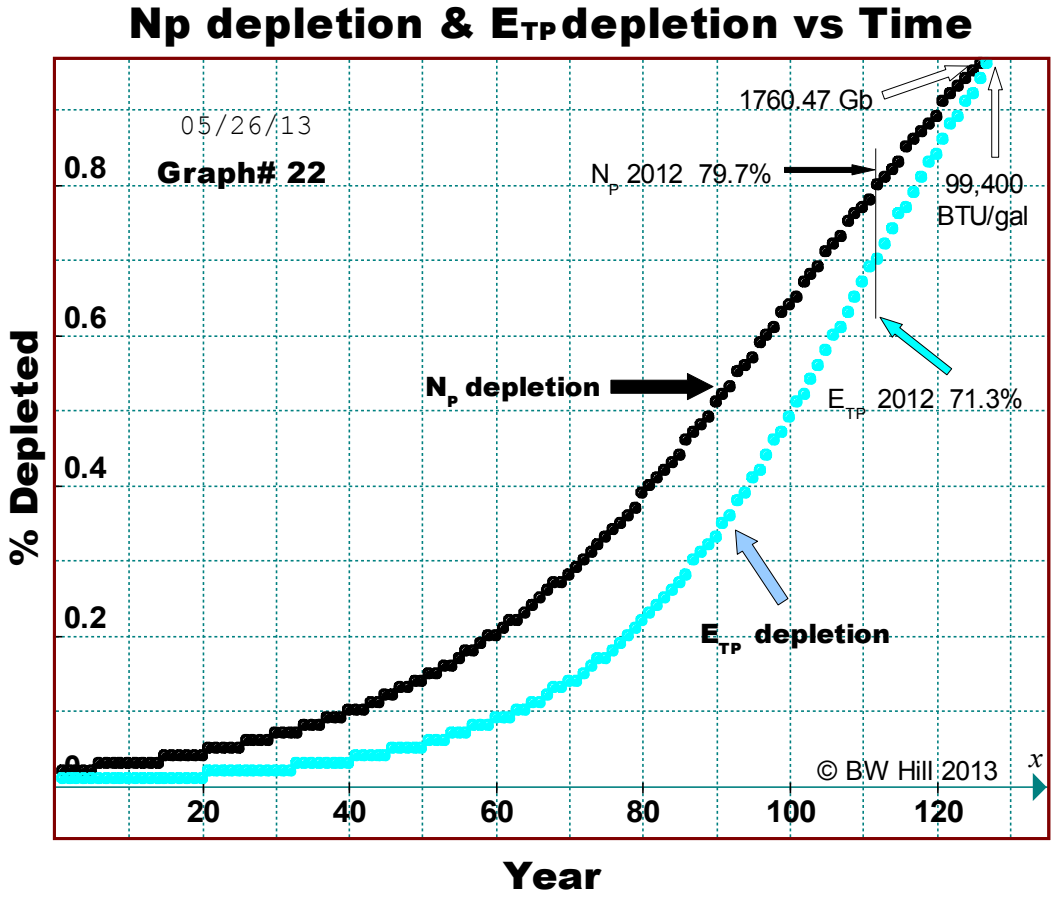
The intersection of the two curves occurs in 2031 (year 131) and at $555/barrel. This intersection is one year from the derived 2030 *Point of Criticality,* and average calculated "dead state" which is shown as the 1760.47 Gb point of *Graph# 4*, and the 99,400 BTU/gal point of *Graph# 8*.


Projected $/b & Max $/b vs Time
05/22/13
Graph# 21
500
400
300
200
100
0
$/barrel
Max $/barrel
2031
555 $/b
Projected
$/barrel
Actual $/barrel
© BW Hill 2013
x
60
80
100
120
Year

Graph#21

8.0 - Depletion:

The depletion status of the world's petroleum reserve can be evaluated from several metrics. In this report we address three that have calculable values. The cumulative production ($\mathbf{N_p}$), the total production energy ($\mathbf{E_{TP}}$), and in dollar terms; Total$\mathbf{E_D}$$, ($/year).

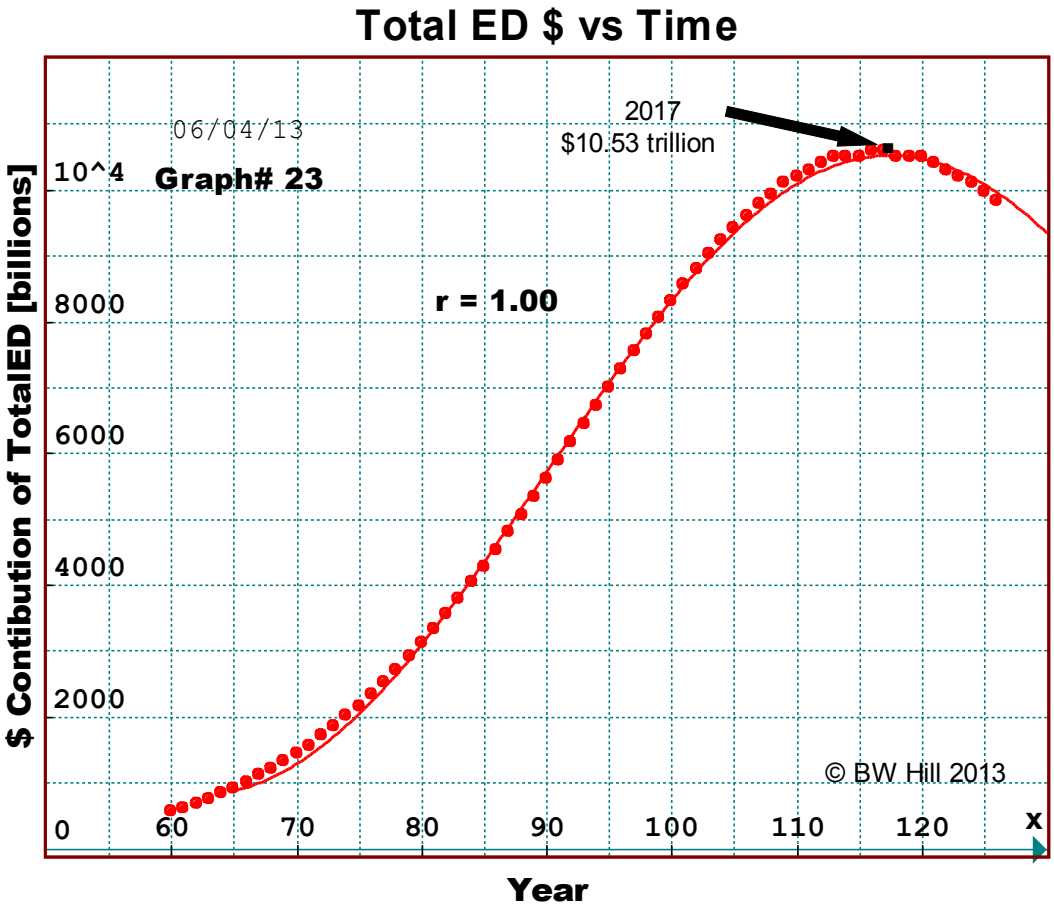


Graph# 22

As can be seen in *Graph# 22* the depletion status of the world's petroleum reserve is dependent upon the metric by which it is measured. The cumulative production ($\mathbf{N_p}$) depletion state is 79.7% as of 2012, whereas the the total production energy ($\mathbf{E_{TP}}$) is 71.3%. This result occurs because $\mathbf{E_{TP}}$ is generated from the entropy production (σ_{cv}) that occurs within the **PPS**. The entropy production of the **PPS** is equal to the heat extracted from the reservoir divided by the reservoir tempertature; this is the

entropy associated with the heat transported out of the reservoir by the mass of the crude, and mass of the water. Both the E_{TP} depletion, and the N_p depletion approach 100% at the 2030 *Point of Criticality*.

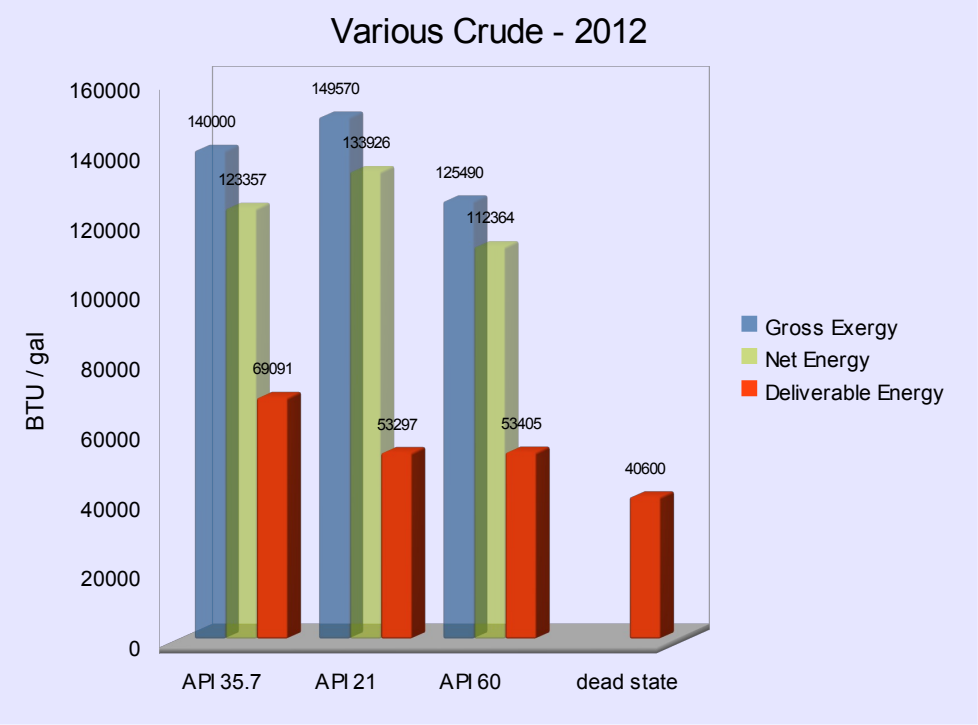
Total E_D\$ represents the total E_D produced per year expressed in dollar terms converted from *Graph# 12*. It is shown in *Graph# 23*. The curve is a sine function, r = 1.00. The curve indicates that the maximum dollar value that will be derived by the end consumer from petroleum will occur in mid 2017 at \$10.526 trillion. It will have fallen to \$9.353 trillion by the time the 2030 *Point of Criticality* is reached. This demonstates that petroleum will remain very valuable to the general economy even during its decline stage. It also suggests that conventional crude, API 30 - 45°, has been setting the average world energy price.



Graph# 23

The depletion status of the world's petroleum reserve is a determination derived from the evaluation of conventional crude (API 30 - 45°). As shown in *Graph# 25,* lighter and heavier crude have lower energy delivery capabilities, thus on a specific volumetric bases, they are not equivalent to conventional crude. The greater majority of petroleum that has been extracted has been conventional crude, and because it delivers a greater amount of energy to the end consumer, it constitutes the overwhelming majority of the economic benefit derived from petroleum. As demonstrated by *Graph# 14* and *Graph# 23* (as both curves were derived from the CDF of conventional crude) the impact of

crude outside the API 30 - 45° range has had no measurable impact on the price, thus the depletion rate,



of the world's petroleum reserve. *Graph# 24* also indicates that crude outside the API 30 - 45° range will reach its average "dead state" prior to conventional.

Graph# 24

The respective energies for three types of crude, depicted by their specific gravities are shown in Graph# 24. 35.7° API represents conventional crude, 21° API represents Mayan Heavy, and 60° API condensates. Mayan Heavy, 21° API, has a lower deliverable energy because of its 28% residual from the refining process that must undergo further vacuum distillation[27]. The values are determined from the ERoEI (*Graph# 15*) of conventional crude. Other crude oils with a higher E_P, such as shale oil, will have lower values.

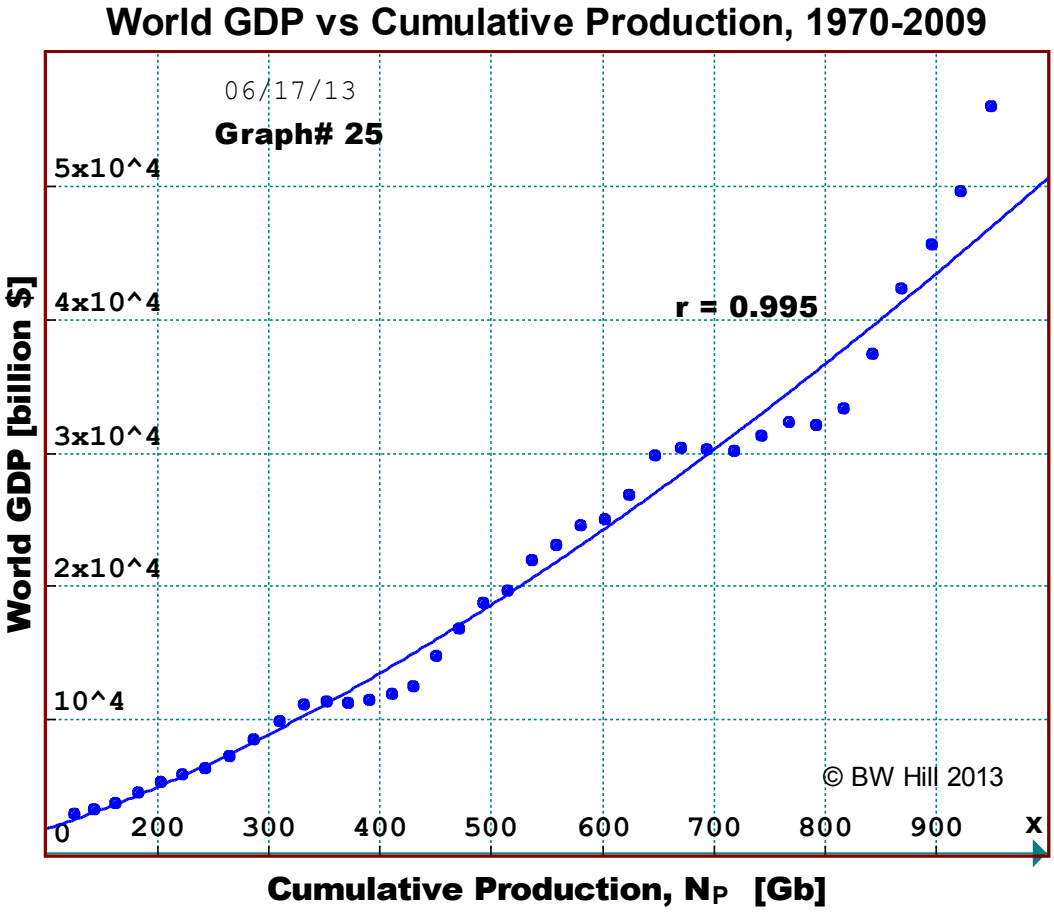
9.0 - Error Analysis:

To derive P_{140} , which is crucial for the development of the E_{TP} function, it is assumed that the EIA data-set reflects an accurate description of historic production. Since, as noted in section **4.3**, the EIA cumulative production values must have been generated from a model; the integrity of that model is examined.

Analysis of major fields, such as the US, UK and Norway[28], where reporting has been consistently

maintained by their various mineral management agencies, indicate that a logistic curve has been followed by the production in these primary areas. Application of Identification Plots to these production areas make it highly unlikely that these distributions are anything other than logistic distributions. Other evidence to support the logistic distribution hypothesis is the EIA's cumulative world production of conventional crude, $\mathbf{P_{140,}}$ plotted against world GDP. $\mathbf{P_{140}}$ encompasses the distribution of crude production within the range of API 30 - 45°. As petroleum is a primary energy provider it can be expected that economic activity would follows its production curve. Cumulative production (the CDF) is a better indicator than yearly production (the PDF) because it accounts for the capital formation that results from petroleum production. *Graph#5* and Graph # 25 give strong support for the distribution determined for $\mathbf{P_{140.}}$

Graph# 25 shows this relationship. World GDP is taken from the World Bank data-set, and cumulative production from the EIA; 1960 = year zero(0) . Graph# 25 is a power function, r = 0.995.

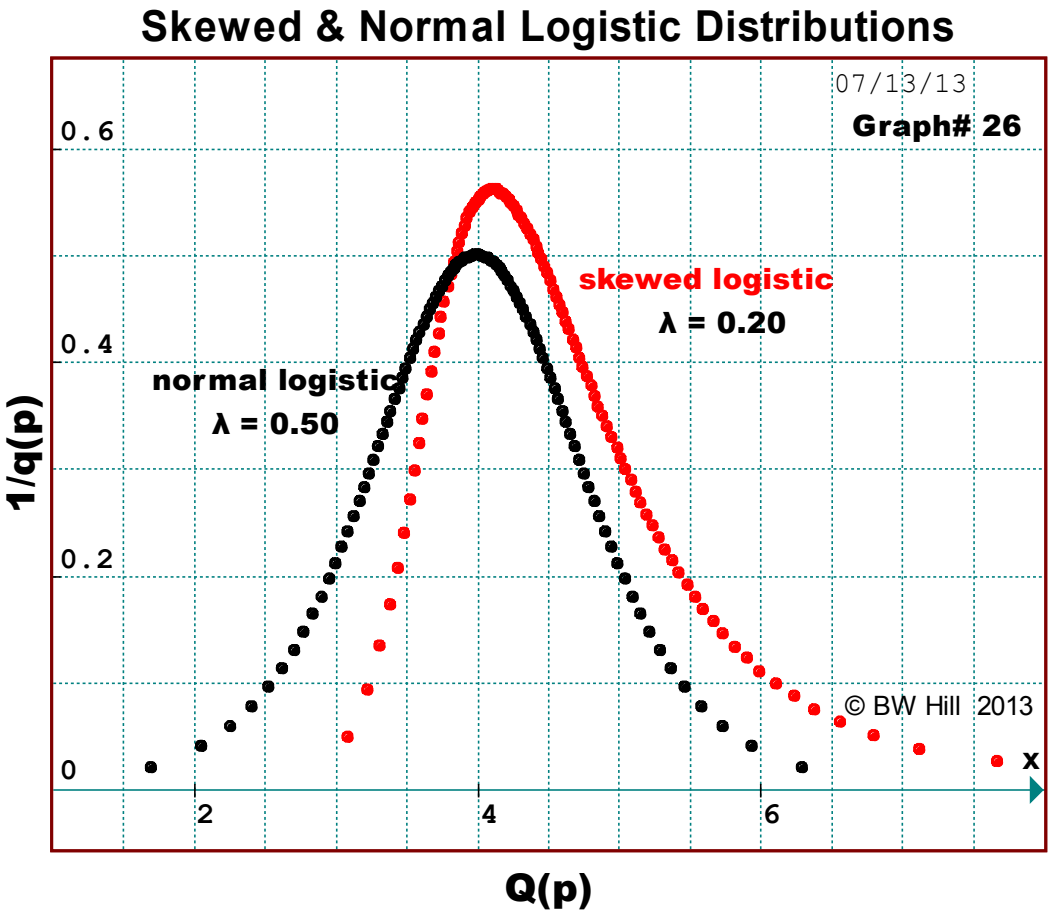


Graph# 25

Although the model employed by the EIA is accurately represented by a logistic distribution, no allowance is made for possible skewness in that distribution[29]. The skewed logistic distribution is

rarely employed because there is no explicit CDF, or PDF for the function. That is, there is no existing mathematical equation to describe it. All calculations must be done numerically which greatly complicates construction of any model. Since the presence of skewness in the distribution could have only been identified for petroleum production in retrospect it is hardly surprising that it has not previously been explored. Indicators such as the long tails of Graph# 3, and the 10.7 year discrepancy between the inflection point of the $\mathbf{E_{TP}}$ curve (Graph#8) and of the inflection point of the CDF of Graph# 2, could only have been identified after the fact.

Even though there is no mathematical equation for a skewed logistic function it can, however, be plotted. Its quantile function is $Q(p) = \lambda \ln(p) - (1-\lambda) \ln(1-p)$ where the skew parameter is $0 \leq \lambda \leq 1$. The PDF is generated by plotting the pair of points $Q(p) = x$, and the inverse of its first derivative, $1/q(p)$. The CDF is generated by plotting the inverse of the quantile function points, p to Q(p). Graph# 26 is an *example* which shows the PDFs of a normal logistic distribution, and a skewed distribution. Both functions produce the same total area under their curves. Black is the normal distribution, red is the skewed distribution. Points are shown because there is no mathematical function to describe the skewed distribution.

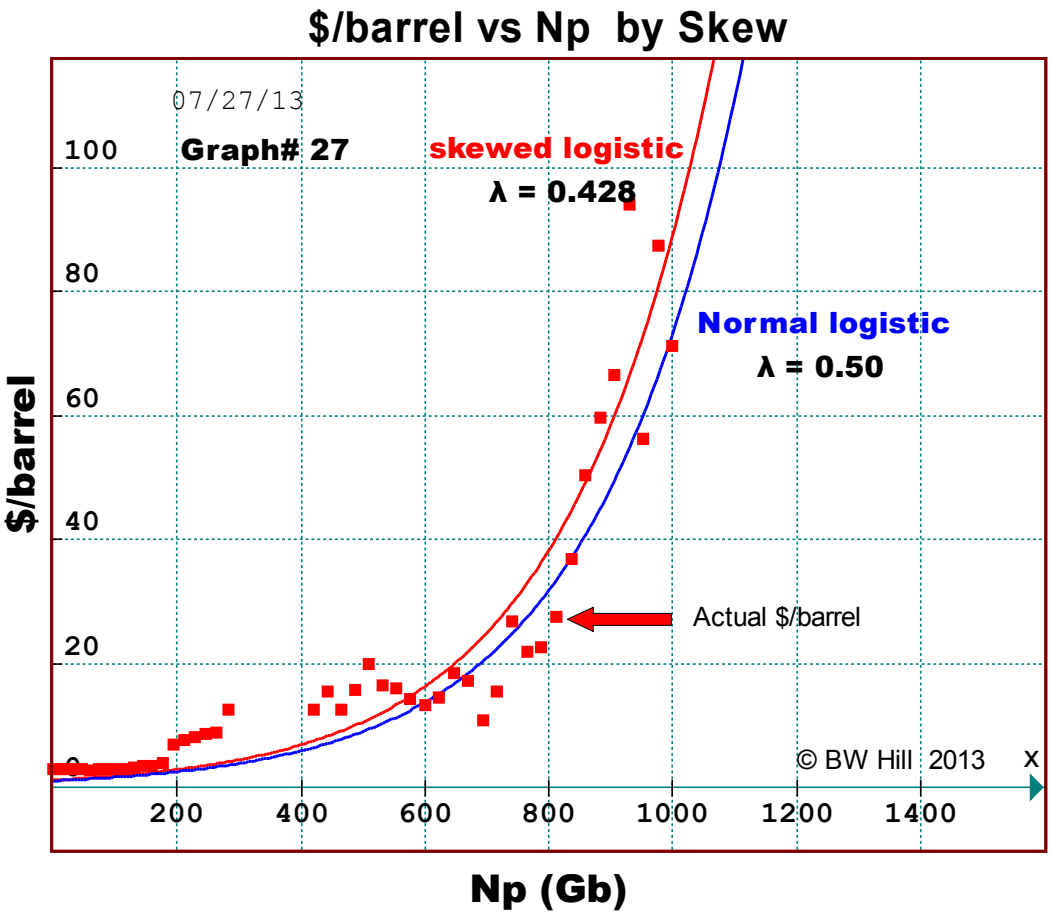


Graph# 26

The inflection point of the CDF for the normal logistic distribution (λ = 0.5) is 2001, for the skewed logistic 2019 (λ = 0.2). **The** red **curve of Graph# 26 is shown only to demonstate the effect of skewness on a distribution**. From the graphs it is obvious that the point of maximum production (known as the peak) can not be determined without knowledge of the skewness in the distribution.

To arrive at an estimate for the skewness present in the cumulative production function, the most reliable data-set available is used for comparison. The data-set employed is the 1960 - 2011 WTI price of crude oil. Graph# 5, $/barrel vs Cumulative Production, gives r = 0.930, which is based on the normal logistic distribution. If a distribution exists that is more accurate than the EIA's it can be expected that it would produce a higher correlation coefficient. It can also be expected that the mean of the difference between the projected $/b - actual $/b will be zero (0) if the skewed distribution exactly fits the actual price data-set.

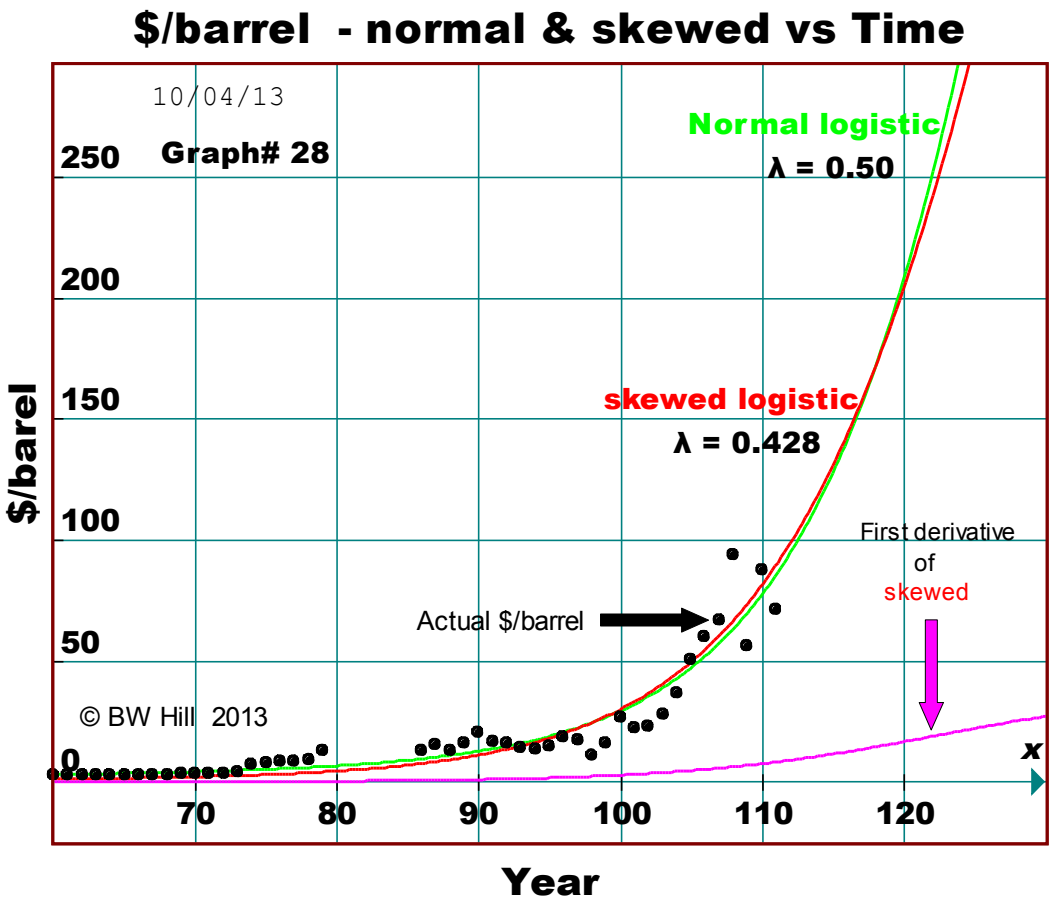
Graph# 27 shows the $/barrel vs Cumulative Production for the normal logistic curve (blue), λ = 0.50, Graph# 5 with r = 0.930, and the skewed logisitc curve (red), λ = 0.428, r = 0.942. The mean of the forty six (46) year difference of (projected $/b - actual $/b) equals $-0.29 for the skewed distribution. For the normal logistic the difference equals $-2.83. The mean of the actual $/barrel for the period equals $20.22, or a difference of 1.4% for the skewed distribution and 14% for the normal. The inflection point of the CDF for the skewed logistic curve occurs in 2006. The 2030 price of crude for the skewed logistic is projected to be $431.91 per barrel; for the normal logistic $499.88 per barrel. The red dots represent actual yearly prices of WTI for 1960 - 2011 as reported by the EIA. 1960 = year zero (0).



Graph#27

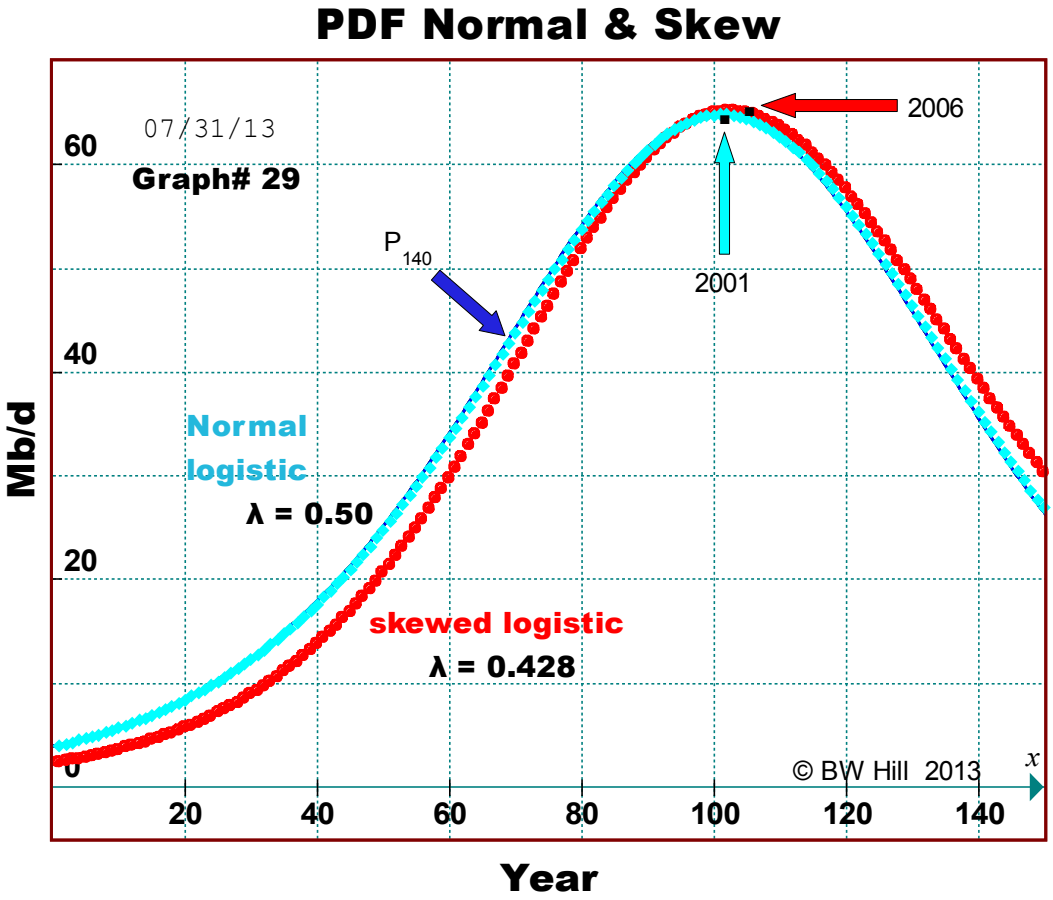
The skewness identified in the cumulative production function indicates that the EIA estimate from their reported production of 897.16 Gb from 1960 to 2005 was 13.97 Gb greater than the actual conventional crude production. The skewed distribution, λ = 0.428, indicates that the 2030 Point of Criticality moves forward to 2035, and results in a daily world production of 43 Mb/d by that date[30]. All points generated from the $\mathbf{P_{140}}$ distribution will be moved forward by about five (5) years. The cumulative production ($\mathbf{N_p}$) depletion state becomes 73.4% as of 2012.

The Price versus Time graphs for the normal logistic, λ = 0.50, and the skewed logistic, λ = 0.428, are shown in Graph# 28.



Graph# 28

The PDFs of the normal logistic, λ = 0.50, and the skewed logisitc, λ = 0.428, are shown in Graph# 29. The $\mathbf{P}_{140}$ curve (dark blue) is plotted over the points generated from the normal logistic quantile function (light blue).



Graph# 29

10.0 - Conclusion:

Only a portion of the world's endogenous petroleum reserve possess the capacity to provide a beneficial component. Determining a reasonably accurate estimate for that quantity has perplexed analysis since

petroleum first became a valuable commercial product. The principal barrier to determining which of the world's 4,300 billion barrels qualifies as being potentially serviceable has rested on the lack of a stable, measurable criteria. Cost has always been considered the Holly Grail of oil production, but cost itself has morphed into its own elusive element. By the time the great Middle Eastern fields came online a production cost of $3 per barrel was considered untenable. Today it is more than $100. As the serviceable portion of the world's petroleum reserve depletes, the cost of producing it has increased in lock step. Obviously, another metric is needed.

The most reasonable parameter by which to judge petroleum's utility is its primary contributing component - ***energy***. Unlike the dollar, an energy unit is a quantity that does not change with time. It also has the advantage of being a developed, mature science, and having a large informational base to describe it. Exergy analysis had its beginnings in the evolution of steam power, more than a hundred and fifty years ago. The principal advantage of using exergy analysis is in its application of the most fundamental laws known to physics; the First and Second Law. They provide constraints that can not be violated!

The constraints imposed by the First and Second Law restrict upper and lower limits. The 99,400 BTU/gal limit that the study shows as being extractable from petroleum is an upper limit. In all probability the value is somewhat less. $\mathbf{P_{140}}$ is limited by $\mathbf{E_G}$ and the entropy production of the **PPS**. Its value can not be more, but it could be less. This implies that the $\mathbf{E_{TP}}$ model is a "best case" scenario. Empirical estimates, however, indicate that it is not far from the mark. One example is the EIA's estimate for petroleum refining energy costs, which they give as 16,300 BTU/$ of finished product. If calculated at $3.00 per gallon for 2012, this produces 48,900 BTU/gal. With 48,000 fields around the world under production, the industry is very competitive. It therefore follows that average extraction costs are close to sale price. Employing the BTU/$ method, the 2012 production energy costs at the well head can be estimated at 14,735 BTU/gal. Distribution costs of raw material, and finished product are estimated at $42/barrel, giving 6,365 BTU/gal. The extraction, processing and distribution energy costs for 2012, when summed, equal 70,000 BTU/gal; which is what the $\mathbf{E_{TP}}$ model predicts. It is therefore concluded that the petroleum industry is operating at an efficiency level that is close to its theoretical limit.

For the petroleum industry to be functioning at a very high level of efficiency should not be surprising. It is a hundred and fifty year old industry, and it has developed a very advanced level of technology. Being producer of the world's most valuable, and critical extractive commodity gave it access to a significant portion of the world's capital inventory. Until *2012*, even though it was experiencing declining conventional crude production, it did not experience declining nominal revenue. The price curve assured that the revenue decline for the industry would not begin until the point of maximum consumer affordability was reached. The non-energy goods producing sector of the economy was contracting because of the lower quantity of energy that was being delivered to it, while the energy producing sector, was in dollar terms, continuing to grow. This ceased to be the situation in 2012 at $104/ barrel.

The 2012 energy half way point initiated a major change in the petroleum production function. It began

a process where the end consumer was no longer able to acquire all the petroleum that the industry produced. More of the energy from petroleum was being committed to the production of petroleum than was being delivered to the consumer. This precipitated the 2014 price decline that reduced prices by 50%. The energy delivered to the end consumer will continue to decline, and the end consumer maximum affordability will decline with it. It will be necessary for the industry to reduce production to compensate. The highest cost production fields will continually be shut in as the price falls below their operating minimum.

The E_{TP} model's predicted rapid decline event is in opposition to the contemporary assumption that production will phase out slowly. The slow decline scenario is known as "sliding down Hubbert's curve". Implied in this belief is the assumption that all barrels of petroleum were made equal in quality, and will remain so in time. Of course this conflicts with the Second Law, and thus can not be an accurate representation of the situation. All barrels were not made with an API of 30-45°, nor is the energy needed to extract, process and distribution them the same over time. It has to increase.

The energy increase that is occurring in petroleum production insures that substitutes for conventional crude will be phased out before the average barrel of conventional crude reaches the dead state. As the energy to produce petroleum increased so did the price to the end consumer. This phase of the price cycle has now ended, and producers will now concentrate on cutting production costs. This will include the very high cost process of replacing reserves that have been extracted.

As the price increased during the prior 2012 cycle, demand for finished products by the non energy goods producing sector of the economy did not diminish. This apparent viloation of the Supply/Demand pricipal occurred because up until 2012 the use of petroleum returned more revenue to the user than it cost them. The use of petroleum was energy positive for the end user; it required less to extract it, and produce its products than it delivered to the economy. After 2012 that was reversed, and demand increases could only result from the energy producing sector. As production begins to decline so also will demand. To keep the the price to the end consumer as affordable as possible refineries will be forced to limit the use of substitutes which are more costly to process. Supply and demand; the supply and demand of energy will limit the extent to which substitutes like extra heavy crude, and shale oil will be used in the future.

The reduced availability of petroleum products, resulting from a reduced per unit value, and a reduced per unit energy delivery ability will have an all encompassing impact on every aspect of contemporary society. It will encompass everyone from the man on the street to the largest organizations. In the United States - federal, state and local governments, along with some private organizations annually invest $2.1 trillion to protect, manage and regulate the flow of petroleum. This includes not only the servicing of its millions of miles of highways, and a vast military infrastructure that is needed to protect the nation's oil supply, trade routes and harbors, but also a myriad of agencies and groups. The MMS, OSHA, EPA, DOT, and an almost endless, and immensely expensive number of regulatory services are involved in the process. As petroleum losses its relevance the unwinding of this labyrinth of colossal enterprises in an orderly and non-chaotic fashion will represent one of the major challenges of the next two decades.

Petroleum depletion is further advanced, and its production will decline faster than generally assumed. Conventional reservoir appraisal methods are founded on First Law premises, but neglect Second Law effects. Although extremely applicative to individual field analysis, when applied to the status of the world's petroleum reserve they produce inconsistent results. In consequence, the last 25% of the world's energy supplying reserve will be orders of magnitude more costly to produce than was the first 25%. The advancing depletion of the world's petroleum reserve could bring about changes of a magnitude that have not been witnessed for millennium! To navigate this conflicting, and difficult era an understanding of the events taking place will be essential. It is our hope that this report will contribute to that endeavor.

The Hill's Group™

Graph Equations

Graph# 2
y = 2123.46 / (1+ 66.92e^(-0.0441x))
y = 2357.15 / (1+ 66.9e^(-0.0414x))

Graph# 3
y = 196.38x + 911.29
y = 199.85x + 762.34

Graph# 4
y = 2000.0 / (1+ 56.7635e^(-0.0414x))
y = 2100.0 / (1+ 59.6016e^(-0.0414x))
y = 2200 / (1+ 62.4398e^(-0.0414x))
y = 2285.65 / (1+ 64.8708e^(-0.0414x))
y = 2300 / (1+ 65.2780e^(-0.0414x))
y = 2400 / (1+ 68.1162e^(-0.0414x))
y = 2500 / (1+ 70.9543e^(-0.0414x))
y = 2600 / (1+ 73.7925e^(-0.0414x))
y = 2700 / (1+ 76.7307e^(-0.0414x))

Graph# 5
y = 7284.18 / (1+ 6569e^(-0.0042x))

Graph# 6
y = 1.25x^5 - 0.5342x^4 - 1.05x^3 - 0.3087x^2 + 1.22x + 0.0472

Graph# 7
y = 8.31x + 3479.19

Graph# 8
y = 1.4*10^5 / (1+ 368.72e^(-0.053x))

Graph#9
y = exp(5.4*10^-5x + 0.6872)

Graph# 10
y = 0.8339x + 2.55

Graph# 11
none

Graph# 12
y = 3.0*10^13 x^-4.72

Graph# 13

y = 3718.85sin (0.2347x + 1.05) + 7701.15

Graph#14
y = 7.4*10^6 x^-0.7158

Graph# 15
y=140000/(1.4*10^5 / (1+ 361.44e^(-0.053x))*0.2045)

Graph# 16
y = 104.06 x^-0.5846

Graph# 17
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 0.6877)

Graph# 18
y = 0.3109x + 0.00043

Graph# 19
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 1.3)
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 0.6877)
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 0.51)

Graph# 20
y = exp(-0.0045x + 12.01)

Graph# 21 chart# 133
y = 598.86 / (1+ 737.15e^(-0.0697x))
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 0.6877)

Graph# 22
none

Graph# 23
y = 4852.96sin (0.0568x + 1.18) + 5672.94 {65,130}

Graph# 24
none

Graph# 25
y = 2.42 x^1.44

Graph# 26
none

Graph# 27
y = 3564.98 / (1+ 2878.83e^(-0.0043x))
y = 7284.18 / (1+ 6569e^(-0.0042x))

Graph#28
y = 3564.98 / (1+ 2878.83e^(-0.0043*(867sin (0.0273x + 3.49) + 799)))
y = exp(5.4*10^-5(1.4*10^5 / (1+ 361.44e^(-0.053x))) + 0.6877)
y=1.0*10^6*e^(-0.0043*(867*sin (0.0273*x + 3.49) + 799))*cos (0.0273*x + 3.49)/((2878.83*e^(-0.0043*(867*sin (0.0273*x + 3.49) + 799)) + 1)^2)

Graph# 29
y=(1000/365)6138.46*e^(-0.0414*x)/((64.87*e^(-0.0414*x) + 1)^2)

Graph# 30
y = 6.3*10^11 x^-7.34

Graph equations may be cut and pasted into a spread sheet. Some modification may be necessary.

They can be cut and pasted without modification into Graphmatica. Graphmatica is a low cost graphics program that provide a wide range of graphing functions for analysis.

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Table 11.5 World Crude Oil Production, 1960-2009
(Million Barrels per Day)

		Selected OPEC [1] Producers								Selected Non-OPEC [1] Producers									
Year	Persian Gulf Nations [2]	Iran	Iraq	Kuwait [3]	Nigeria	Saudi Arabia [3]	United Arab Emirates	Venezuela	Total OPEC [4]	Canada	China	Mexico	Norway	Former U.S.S.R.	Russia	United Kingdom	United States	Total Non-OPEC [4]	World
1960	5.27	1.07	0.97	1.69	0.02	1.31	0.00	2.85	8.27	0.52	0.10	0.27	0.00	2.91	– –	(s)	7.04	12.72	20.99
1961	5.65	1.20	1.01	1.74	.05	1.48	.00	2.92	8.93	.61	.11	.29	.00	3.28	– –	(s)	7.18	13.52	22.45
1962	6.19	1.33	1.01	1.96	.07	1.64	.01	3.20	10.05	.67	.12	.31	.00	3.67	– –	(s)	7.33	14.30	24.35
1963	6.82	1.49	1.16	2.10	.08	1.79	.05	3.25	11.07	.71	.13	.31	.00	4.07	– –	(s)	7.54	15.06	26.13
1964	7.61	1.71	1.26	2.30	.12	1.90	.19	3.39	12.52	.75	.18	.32	.00	4.60	– –	(s)	7.61	15.66	28.18
1965	8.37	1.91	1.32	2.36	.27	2.21	.28	3.47	13.86	.81	.23	.32	.00	4.79	– –	(s)	7.80	16.47	30.33
1966	9.32	2.13	1.39	2.48	.42	2.60	.36	3.37	15.29	.88	.29	.33	.00	5.23	– –	(s)	8.30	17.67	32.96
1967	9.91	2.60	1.23	2.50	.32	2.81	.38	3.54	16.29	.96	.28	.36	.00	5.68	– –	(s)	8.81	19.11	35.39
1968	10.91	2.84	1.50	2.61	.14	3.04	.50	3.60	18.11	1.19	.30	.39	.00	6.08	– –	(s)	9.10	20.53	38.63
1969	11.95	3.38	1.52	2.77	.54	3.22	.63	3.59	20.11	1.13	.48	.46	.00	6.48	– –	(s)	9.24	21.59	41.70
1970	13.39	3.83	1.55	2.99	1.08	3.80	.78	3.71	22.56	1.26	.60	.49	.00	6.99	– –	(s)	9.64	23.32	45.89
1971	15.77	4.54	1.69	3.20	1.53	4.77	1.06	3.55	24.41	1.35	.78	.49	.01	7.48	– –	(s)	9.46	24.10	48.52
1972	17.54	5.02	1.47	3.28	1.82	6.02	1.20	3.22	26.03	1.53	.90	.51	.03	7.89	– –	(s)	9.44	25.11	51.14
1973	20.67	5.86	2.02	3.02	2.05	7.60	1.53	3.37	29.66	1.80	1.09	.47	.03	8.32	– –	(s)	9.21	26.02	55.68
1974	21.28	6.02	1.97	2.55	2.26	8.48	1.68	2.98	29.32	1.55	1.32	.57	.04	8.91	– –	(s)	8.77	26.39	55.72
1975	18.93	5.35	2.26	2.08	1.78	7.08	1.66	2.35	25.79	1.43	1.49	.71	.19	9.52	– –	.01	8.37	27.04	52.83
1976	21.51	5.88	2.42	2.15	2.07	8.58	1.94	2.29	29.12	1.31	1.67	.83	.28	10.06	– –	.25	8.13	28.23	57.34
1977	21.73	5.66	2.35	1.97	2.09	9.25	2.00	2.24	29.58	1.32	1.87	.98	.28	10.60	– –	.77	8.24	30.12	59.71
1978	20.61	5.24	2.56	2.13	1.90	8.30	1.83	2.17	28.16	1.32	2.08	1.21	.36	11.11	– –	1.08	8.71	32.00	60.16
1979	21.07	3.17	3.48	2.50	2.30	9.53	1.83	2.36	29.35	1.50	2.12	1.46	.40	11.38	– –	1.57	8.55	33.32	62.67
1980	17.96	1.66	2.51	1.68	2.06	9.90	1.71	2.17	25.38	1.44	2.11	1.94	.49	11.71	– –	1.62	8.60	34.17	59.56
1981	15.25	1.38	1.00	1.13	1.43	9.82	1.47	2.10	21.22	1.29	2.01	2.31	.47	11.85	– –	1.81	8.57	34.83	56.05
1982	12.16	2.21	1.01	.82	1.30	6.48	1.25	1.90	17.77	1.27	2.05	2.75	.49	11.91	– –	2.07	8.65	35.68	53.45
1983	11.08	2.44	1.01	1.06	1.24	5.09	1.15	1.80	16.57	1.36	2.12	2.69	.61	11.97	– –	2.29	8.69	36.69	53.26
1984	10.78	2.17	1.21	1.16	1.39	4.66	1.15	1.80	16.50	1.44	2.30	2.78	.71	11.86	– –	2.48	8.88	38.00	54.50
1985	9.63	2.25	1.43	1.02	1.50	3.39	1.19	1.68	15.37	1.47	2.51	2.75	.77	11.59	– –	2.53	8.97	38.60	53.97
1986	11.70	2.04	1.69	1.42	1.47	4.87	1.33	1.79	17.46	1.47	2.62	2.44	.84	11.90	– –	2.54	8.68	38.74	56.20
1987	12.10	2.30	2.08	1.59	1.34	4.27	1.54	1.75	17.71	1.54	2.69	2.55	.98	12.05	– –	2.41	8.35	38.92	56.63
1988	13.46	2.24	2.69	1.49	1.45	5.09	1.57	1.90	19.74	1.62	2.73	2.51	1.11	12.05	– –	2.23	8.14	38.96	58.69
1989	14.84	2.81	2.90	1.78	1.72	5.06	1.86	1.91	21.40	1.56	2.76	2.52	1.48	11.72	– –	1.80	7.61	38.40	59.79
1990	15.28	3.09	2.04	1.18	1.81	6.41	2.12	2.14	22.49	1.55	2.77	2.55	1.63	10.98	– –	1.82	7.36	38.00	60.49
1991	14.74	3.31	.31	.19	1.89	8.12	2.39	2.38	22.48	1.55	2.84	2.68	1.87	9.99	– –	1.80	7.42	37.71	60.19
1992	15.97	3.43	.43	1.06	1.94	8.33	2.27	2.37	23.74	1.61	2.85	2.67	2.13	– –	7.63	1.83	7.17	36.37	60.12
1993	16.71	3.54	.51	1.85	1.96	8.20	2.16	2.45	24.46	1.68	2.89	2.67	2.28	– –	6.73	1.92	6.85	35.71	60.17
1994	16.96	3.62	.55	2.03	1.93	8.12	2.19	2.59	24.90	1.75	2.94	2.69	2.57	– –	6.14	2.37	6.66	36.20	61.10
1995	17.21	3.64	.56	2.06	1.99	8.23	2.23	2.75	25.54	1.81	2.99	2.62	2.77	– –	6.00	2.49	6.56	36.85	62.38
1996	17.37	3.69	.58	2.06	2.00	8.22	2.28	2.94	26.02	1.84	3.13	2.86	3.09	– –	5.85	2.57	6.46	37.73	63.75
1997	18.10	3.66	1.16	2.01	2.13	8.36	2.32	3.28	27.29	1.92	3.20	3.02	3.14	– –	5.92	2.52	6.45	38.45	65.74
1998	19.34	3.63	2.15	2.09	2.15	8.39	2.35	3.17	28.37	1.98	3.20	3.07	3.01	– –	5.85	2.62	6.25	38.60	66.97
1999	18.67	3.56	2.51	1.90	2.13	7.83	2.17	2.83	27.22	1.91	3.20	2.91	3.02	– –	6.08	2.68	5.88	38.70	65.92
2000	19.89	3.70	2.57	2.08	2.17	8.40	2.37	3.16	28.98	1.98	3.25	3.01	3.22	– –	6.48	2.28	5.82	39.52	68.49
2001	19.10	3.72	2.39	2.00	2.26	8.03	2.21	3.01	28.16	2.03	3.30	3.13	3.23	– –	6.92	2.28	5.80	39.94	68.10
2002	17.79	3.44	2.02	1.89	2.12	7.63	2.08	2.60	26.39	2.17	3.39	3.18	3.13	– –	7.41	2.29	5.75	40.77	67.16
2003	19.06	3.74	1.31	2.14	2.28	8.78	2.35	2.34	27.98	2.31	3.41	3.37	3.04	– –	8.13	2.09	5.68	41.45	69.43
2004	20.79	4.00	2.01	2.38	2.33	9.10	2.48	2.56	30.41	2.40	3.49	3.38	2.95	– –	8.80	1.85	5.42	R42.07	R72.48
2005	21.50	4.14	1.88	2.53	2.63	9.55	2.54	2.56	31.87	2.37	3.61	3.33	2.70	– –	9.04	1.65	5.18	R41.85	R73.72
2006	21.23	4.03	2.00	2.54	2.44	9.15	2.64	2.51	31.59	2.53	3.67	3.26	2.49	– –	9.25	1.49	5.10	R41.84	R73.44
2007	20.67	3.91	2.09	2.46	2.35	8.72	2.60	2.43	31.21	R2.63	3.73	3.08	2.27	– –	9.44	1.50	5.06	R41.78	R72.99
2008	R21.91	R4.05	R2.38	2.58	2.17	9.26	2.68	2.39	R32.48	R2.60	3.79	2.79	2.18	– –	9.36	1.39	R4.95	R41.21	R73.69
2009[P]	20.40	4.04	2.39	2.35	2.21	8.25	2.41	2.24	30.65	2.56	3.80	2.60	2.07	– –	9.50	1.33	5.31	41.61	72.26

R=Revised. P=Preliminary. – – = Not applicable. (s)=Less than 0.005 million barrels per day.

[1] See "Organization of the Petroleum Exporting Countries (OPEC)" in Glossary. On this table, countries are classified as "OPEC" or "Non-OPEC" in all years based on their membership status as of January 1, 2009.

[2] Bahrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, and the Neutral Zone (between Kuwait and Saudi Arabia).

[3] Includes about one-half of the production in the Neutral Zone between Kuwait and Saudi Arabia.

[4] On this table, "Total OPEC" for all years includes Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, Venezuela, and the Neutral Zone (between Kuwait and Saudi Arabia). Data for all countries not included in "Total OPEC" are included in "Total Non-OPEC."

Notes: • Data are for crude oil, including extra heavy crude oil, lease condensate, and liquids processed from Canadian oil sands; they exclude natural gas plant liquids. • Totals may not equal sum of components due to independent rounding.
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Table 11.1 World Primary Energy Production by Source, 1970-2007
(Quadrillion Btu)

Year	Coal	Natural Gas [1]	Crude Oil [2]	Natural Gas Plant Liquids	Nuclear Electric Power [3]	Hydroelectric Power [3]	Geothermal [3] and Other [4]	Total
1970	62.96	37.09	97.09	3.61	0.90	12.15	1.59	215.39
1971	61.72	39.80	102.70	3.85	1.23	12.74	1.61	223.64
1972	63.65	42.08	108.52	4.09	1.66	13.31	1.68	234.99
1973	63.87	44.44	117.88	4.23	2.15	13.52	1.73	247.83
1974	63.79	45.35	117.82	4.22	2.86	14.84	1.76	250.64
1975	66.20	45.67	113.08	4.12	3.85	15.03	1.74	249.69
1976	67.32	47.62	122.92	4.24	4.52	15.08	1.97	263.67
1977	68.46	48.85	127.75	4.40	5.41	15.56	2.11	272.54
1978	69.56	50.26	128.51	4.55	6.42	16.80	2.32	278.41
1979	73.83	53.93	133.87	4.87	6.69	17.69	2.48	293.36
1980	R71.17	R54.76	128.04	5.10	7.58	17.90	R3.03	R287.58
1981	R71.65	R55.57	120.11	5.37	8.53	18.26	R3.13	282.61
1982	R74.20	55.49	114.45	5.35	9.51	18.71	R3.41	281.13
1983	74.33	R56.11	113.98	5.36	10.72	19.69	3.58	R283.77
1984	R78.55	R61.76	116.88	5.73	12.99	20.19	R3.64	R299.73
1985	R82.25	R64.12	115.37	5.83	15.30	R20.39	R3.84	R307.11
1986	R84.25	R65.33	120.18	6.15	18.25	R20.81	R3.89	R316.85
1987	86.10	R68.46	121.06	6.35	17.64	R20.80	3.84	R324.26
1988	R88.16	R71.85	125.84	6.65	19.23	R21.40	R4.16	R337.28
1989	R89.43	R74.28	127.83	6.69	19.74	R21.49	R4.53	R343.99
1990	R90.88	R76.14	129.35	6.87	20.36	R22.31	R4.12	R350.02
1991	R88.33	R76.98	128.73	7.12	21.18	R22.78	4.08	R347.20
1992	R85.79	R77.21	128.93	7.17	21.28	R22.63	R4.41	R347.43
1993	R84.05	78.59	128.72	7.47	22.01	R23.85	R4.45	R349.14
1994	R85.98	79.35	130.69	8.10	22.41	R24.10	R4.67	R355.30
1995	R87.99	80.42	133.43	8.40	23.26	R25.29	4.71	R363.51
1996	R88.49	R84.19	136.73	8.59	24.11	R25.74	R4.93	R372.78
1997	R92.14	84.11	140.63	8.79	23.88	R26.01	R5.04	R380.60
1998	R90.76	85.75	143.24	9.02	24.32	R26.00	R5.04	R384.13
1999	R89.85	87.66	140.96	9.26	25.09	R26.50	R5.27	R384.58
2000	R89.10	R90.96	R146.82	9.63	25.65	R26.73	R5.45	R394.35
2001	R93.87	R92.84	145.57	10.10	26.39	R26.50	R5.31	R400.58
2002	R97.58	R95.87	R143.52	10.28	26.67	R26.46	R5.64	R406.01
2003	R105.30	R97.64	R148.40	10.74	26.37	R26.73	R6.09	R421.27
2004	R116.60	R100.14	R155.35	11.10	27.32	R27.84	R6.60	R444.94
2005	R123.03	R103.24	R157.63	11.47	27.54	R28.91	R7.35	R459.17
2006	R127.60	R106.65	R157.02	11.68	27.76	R29.74	R7.24	R467.67
2007P	132.73	108.98	156.00	11.89	27.10	29.64	8.80	475.15

[1] Dry production.

[2] Includes lease condensate.

[3] Net generation, i.e., gross generation less plant use.

[4] Includes net electricity generation from wood, waste, solar, and wind. Data for the United States also include other renewable energy.

R=Revised. P=Preliminary.

Notes: • Data in this table do not include recent updates for the United States (see Table 1.2) or for other countries (see http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm). • See Note 1, "World Primary Energy Production," at end of section. • Totals may not equal sum of components due to independent rounding.

Web Page: For related information, see http://www.eia.gov/international.

Sources: • 1970-1979—U.S. Energy Information Administration (EIA), International Energy Database. • 1980 forward—EIA, International Energy Statistics, March 9, 2010.

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