The future of mining: an energy analysis

Ugo Bardi

Native metals

Native copper

Gold nugget

Chalcopyrite deposits, $CuFeS_2$: 34.5% copper when pure.

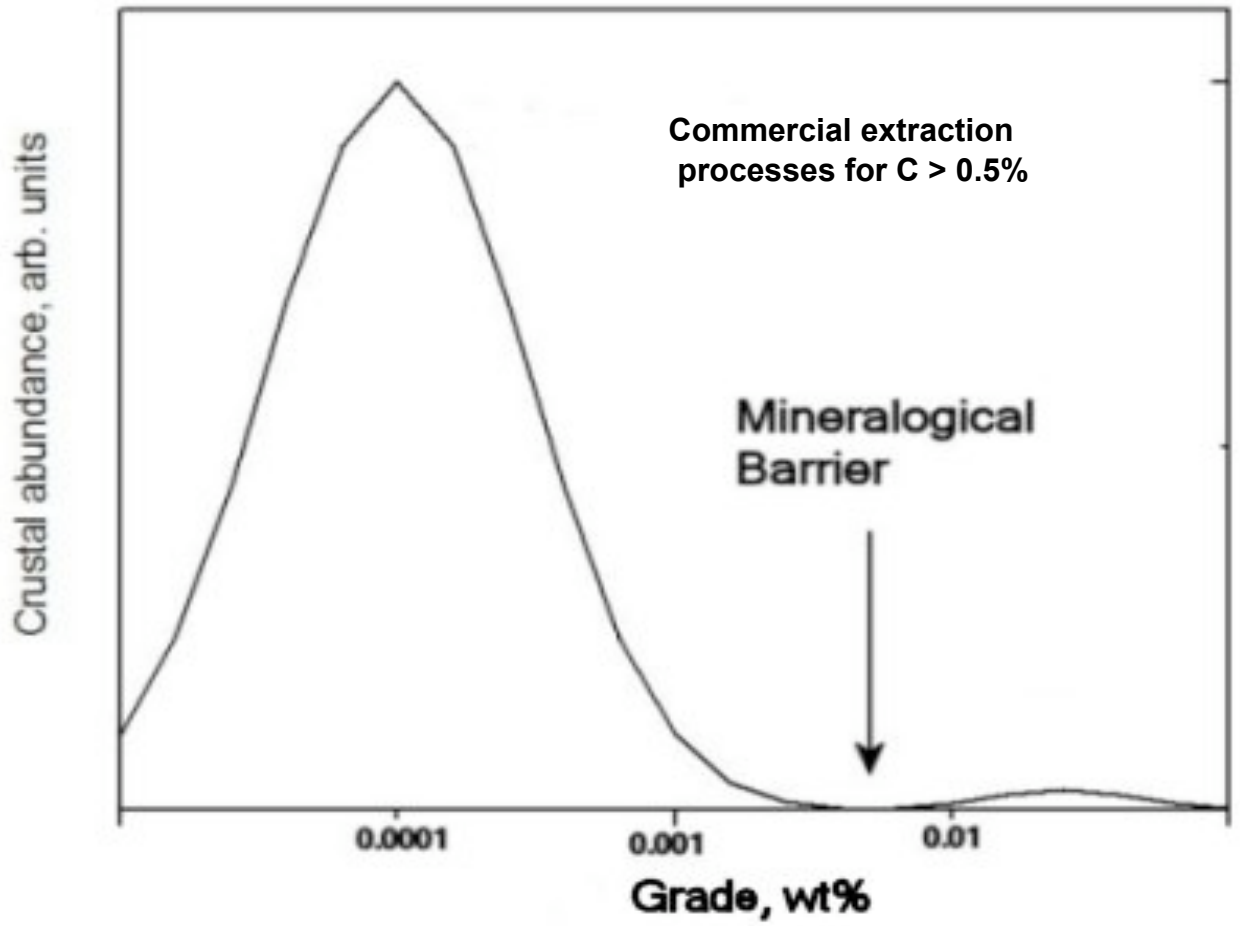
Typical ores ~ 1% copper in weight

Mining machines


Morency copper mine, Australia

Tailings, Bingham copper mine, UT

The mineralogical barrier according to B.W. Skinner, 1976



57 elements listed by USGS as being commercially extracted

Total mass extracted: ca. 10 E+11 tons/year

Total sedimentation in the oceans ca. 2 E+10 tons/year

Metal	Specific production energy MJ/kg	World production (Mtons/year)	Total energy used (EJ)
Steel	22	1100	24
Aluminium	211	33	6.963
Copper	48	15	0.72
Zinc	42	10	0.42
Nickel	160	1.4	0.224
lead	26	3	0.078

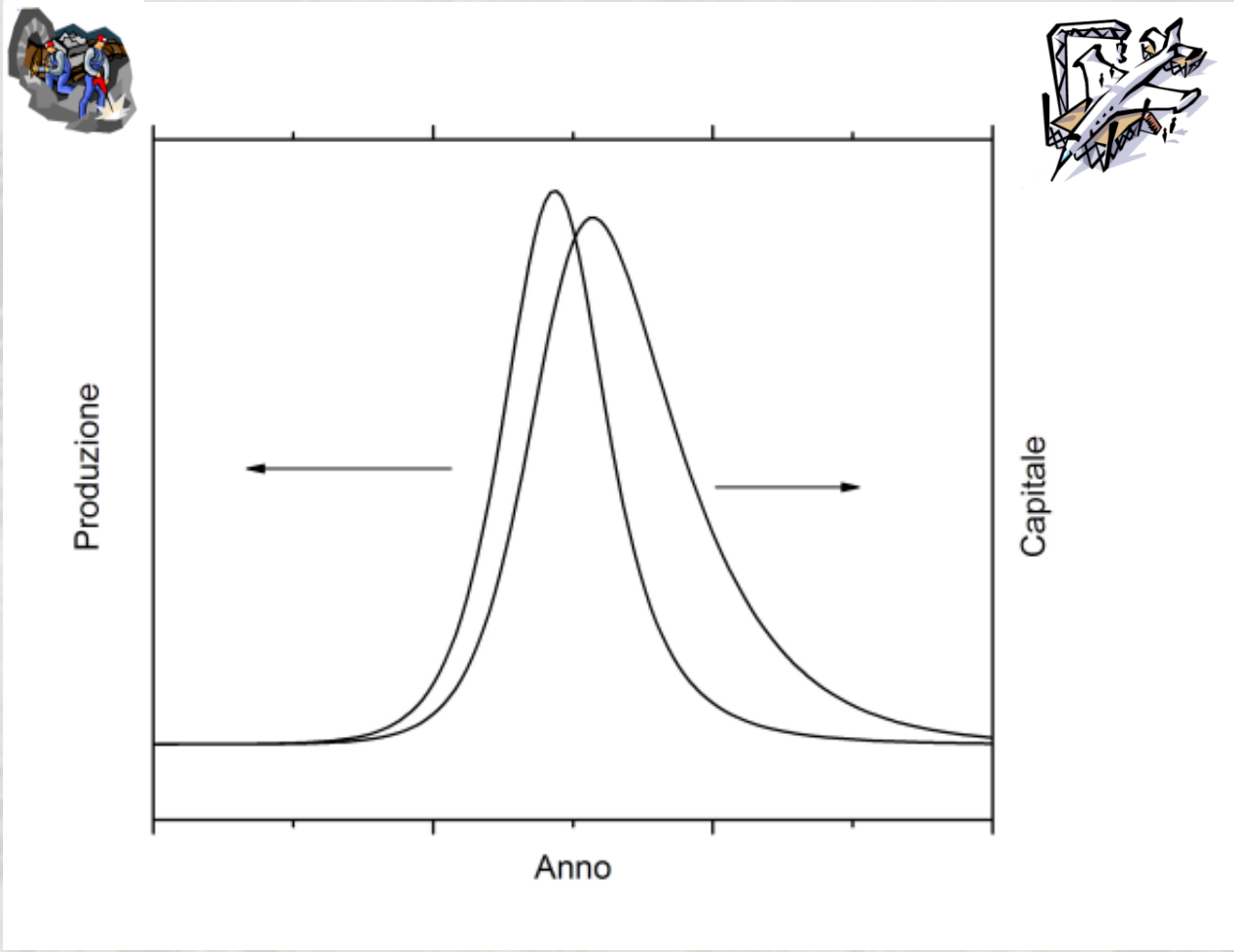
Total world primary energy: ~ 420 EJ

Data from Norgate and Rankin (2002) and from USGS (2005)

Simple Dynamic Modelling

$$p = -k_1 CR$$

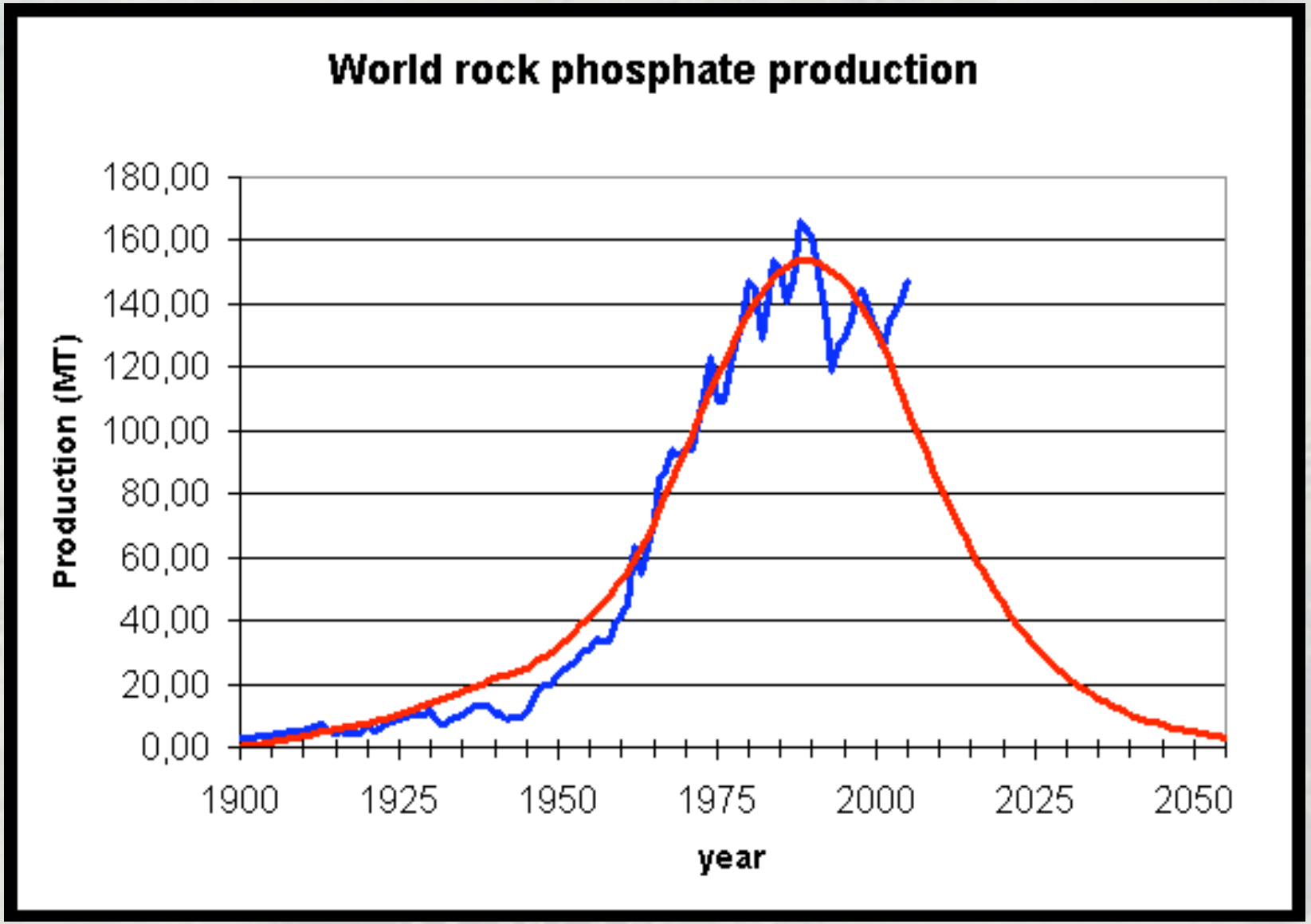
$$g = k_2 CR - k_3 C$$



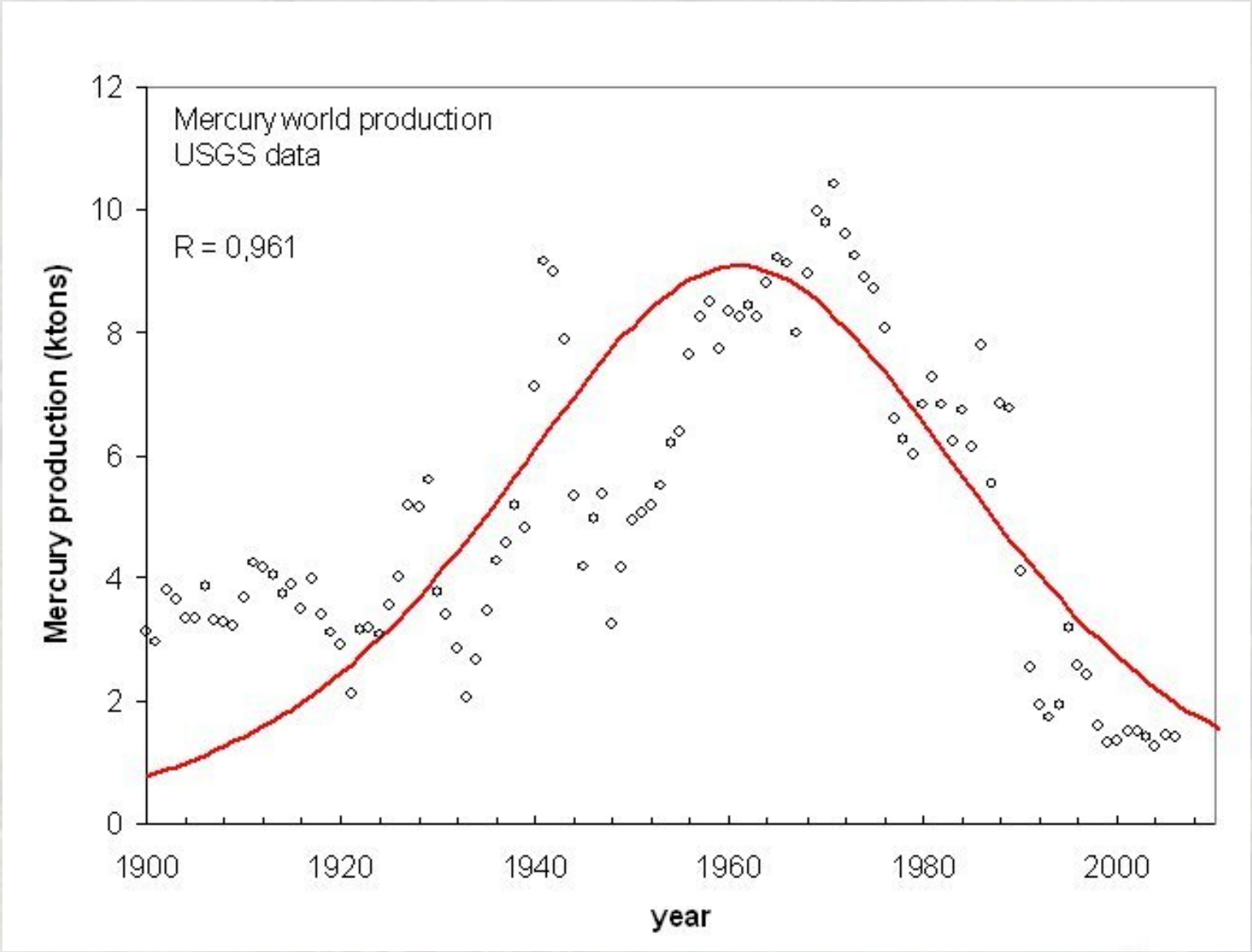
p = production
g = capital growth

C = Capital
R = Resources

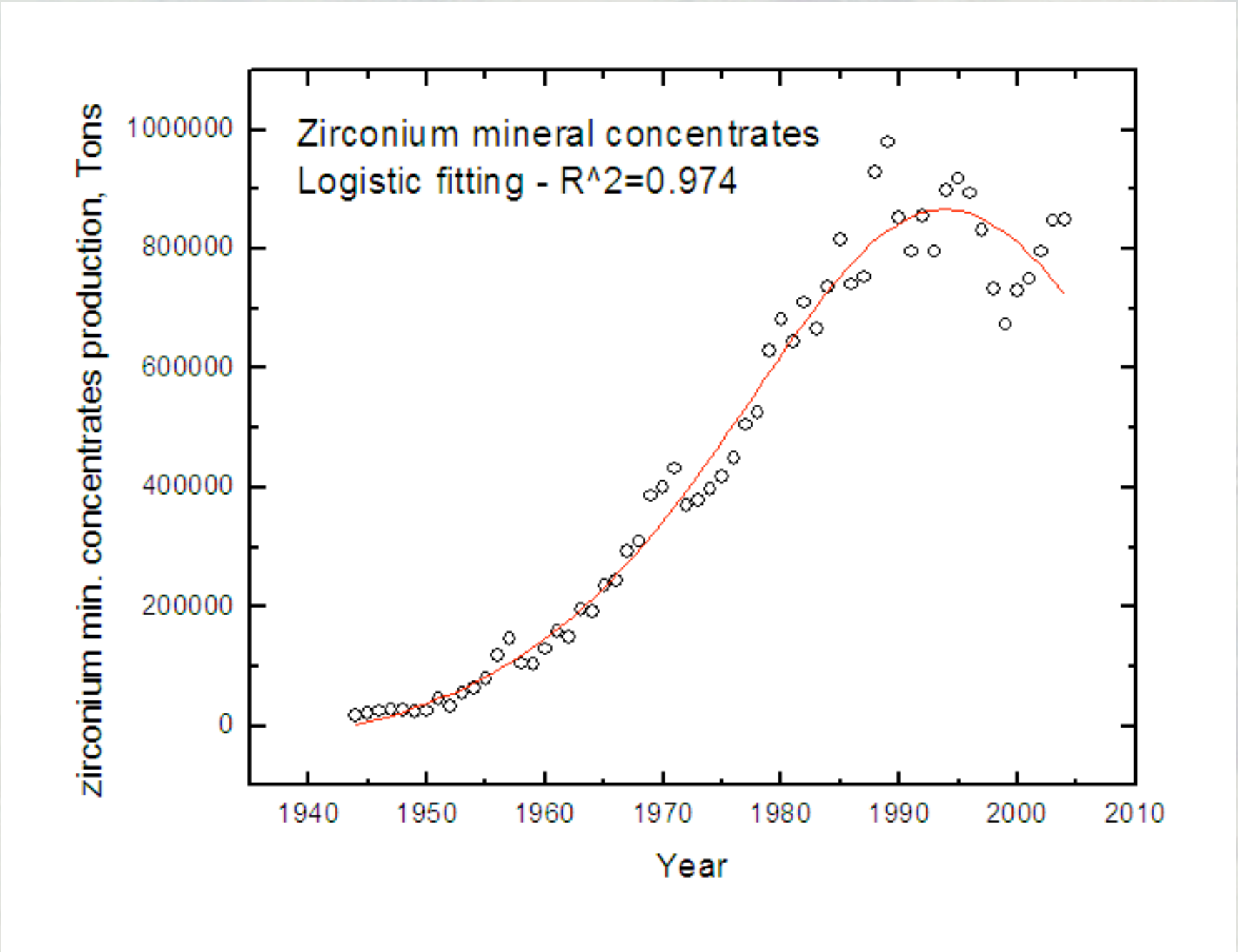
k_1 = efficiency of transformation of capital into resources
k_2 = efficiency of transformation of resources into capital
k_3 = capital depreciation



Dery and Anderson, The Oil Drum 2007
http://www.theoildrum.com/node/2882



Bardi and Pagani, TOD 2007
http://europe.theoildrum.com/node/3086



Bardi and Pagani, TOD 2007
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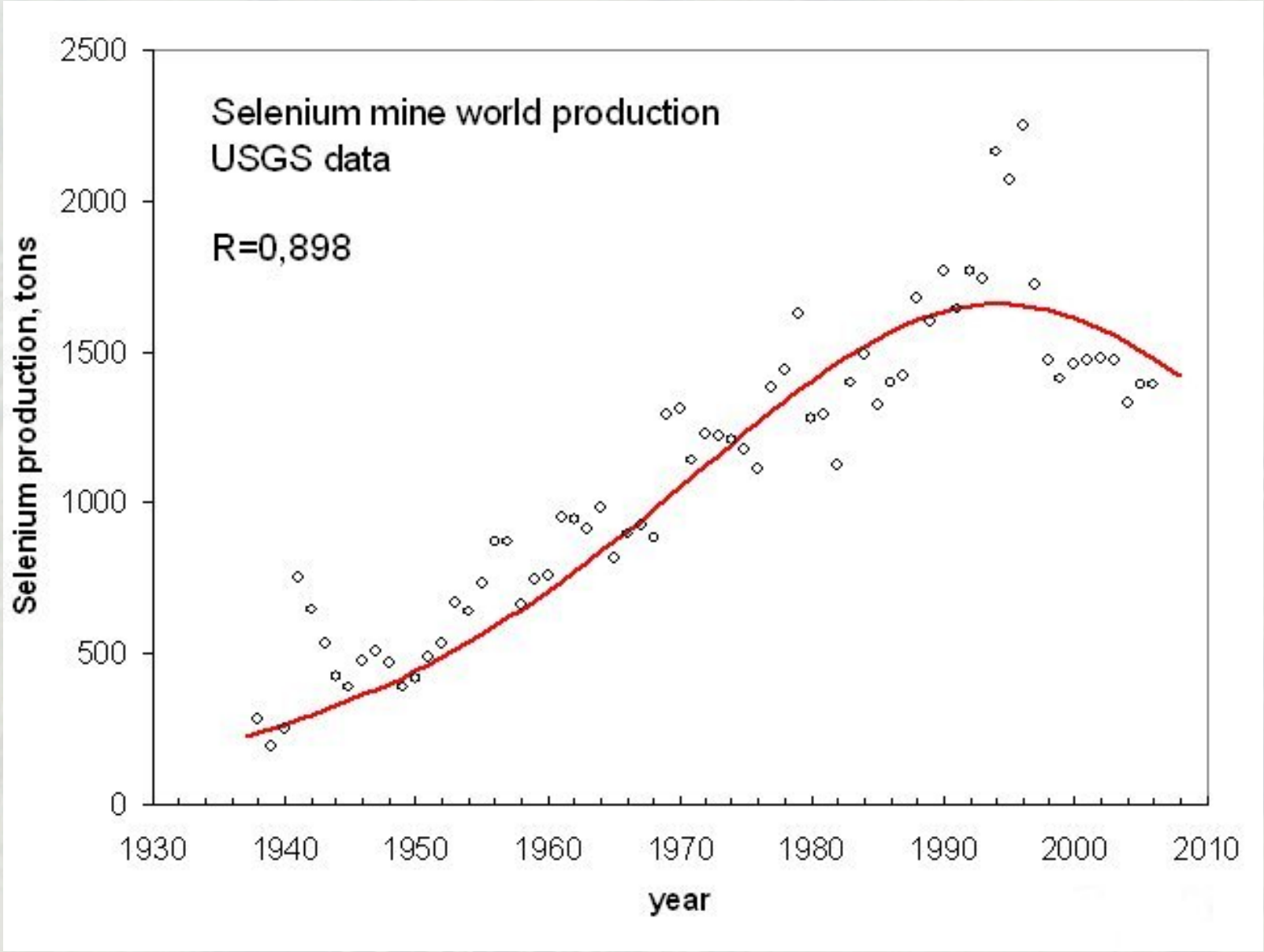

Bardi and Pagani, TOD 2007
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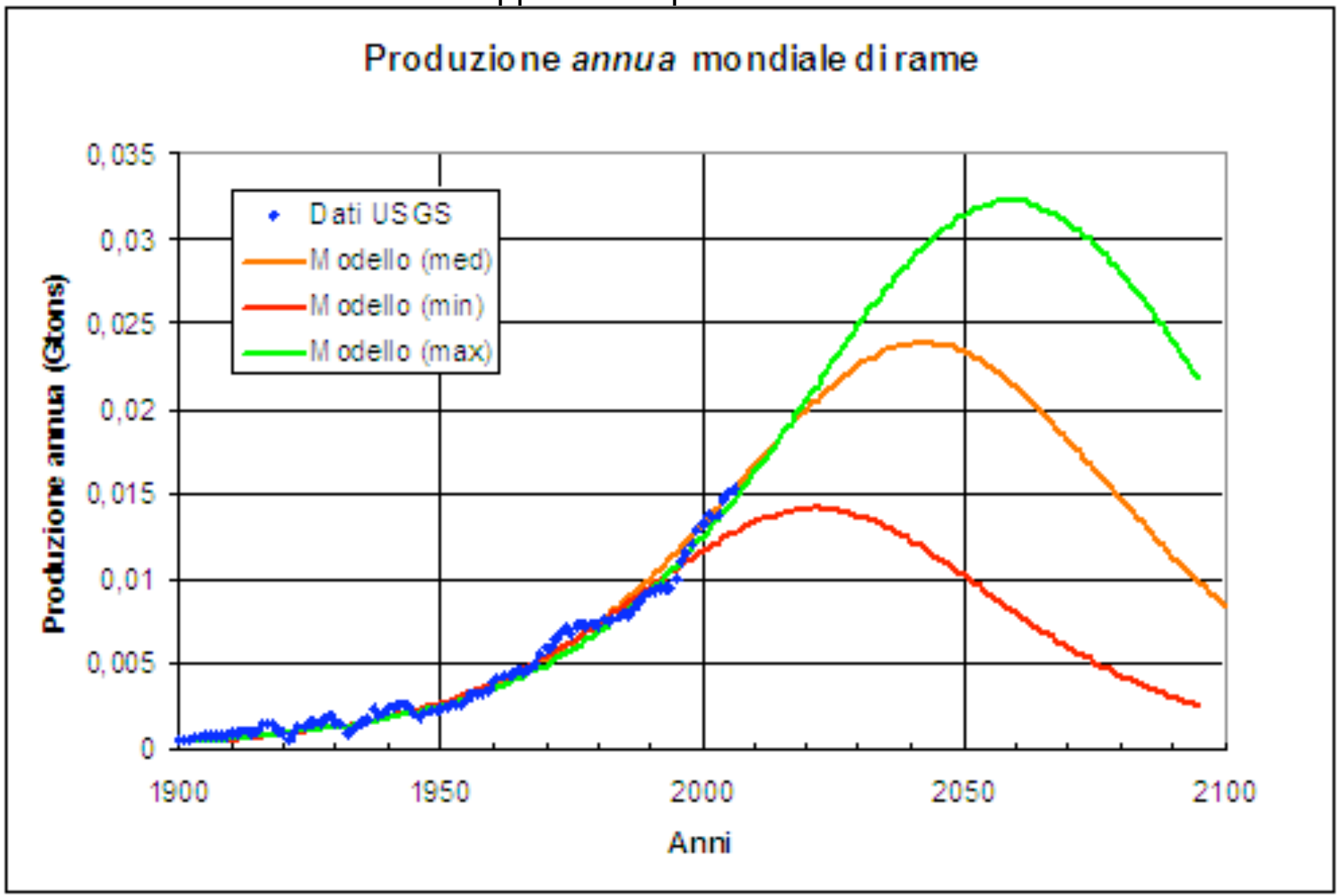
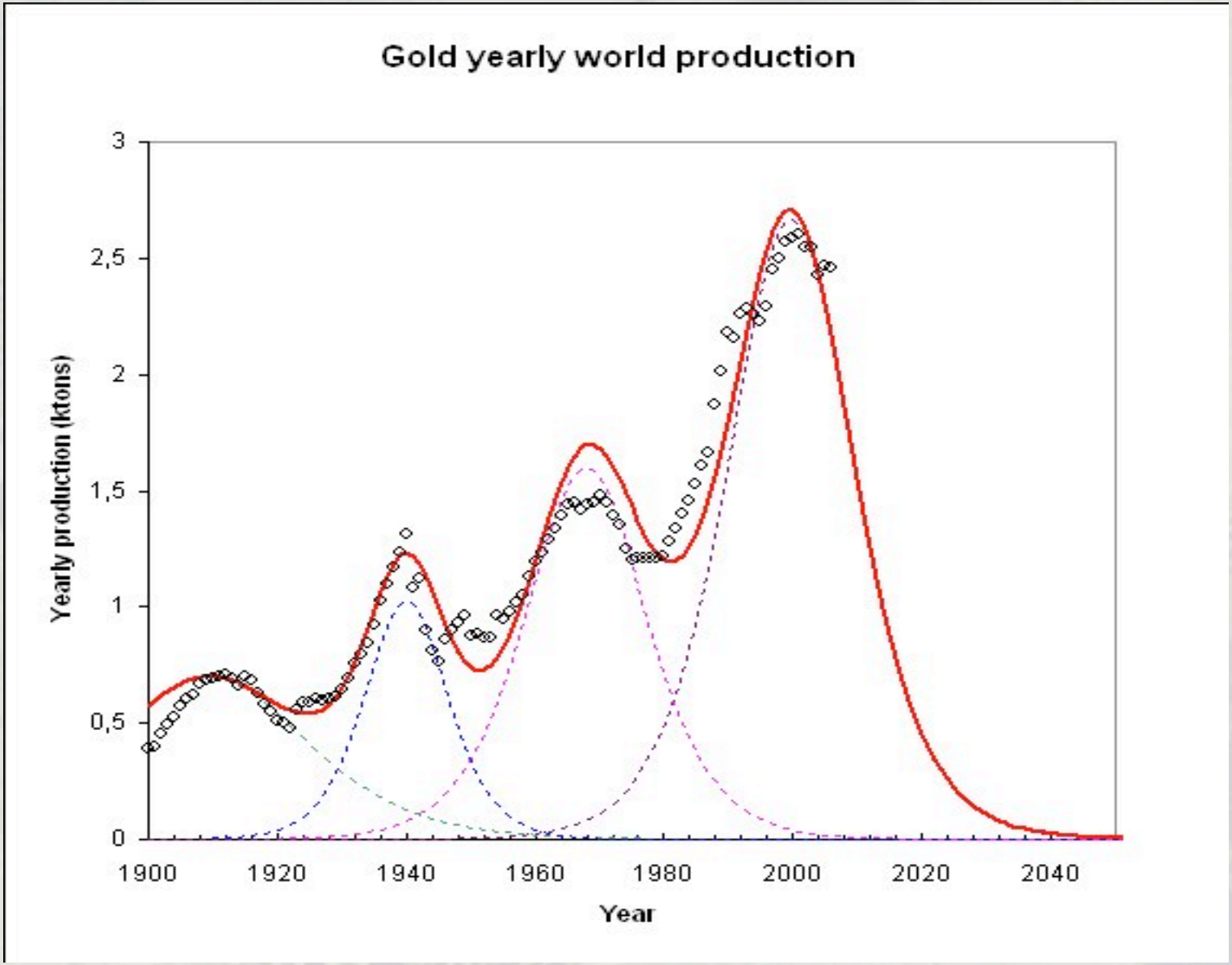
Copper world production



Bardi and Pagani 2007

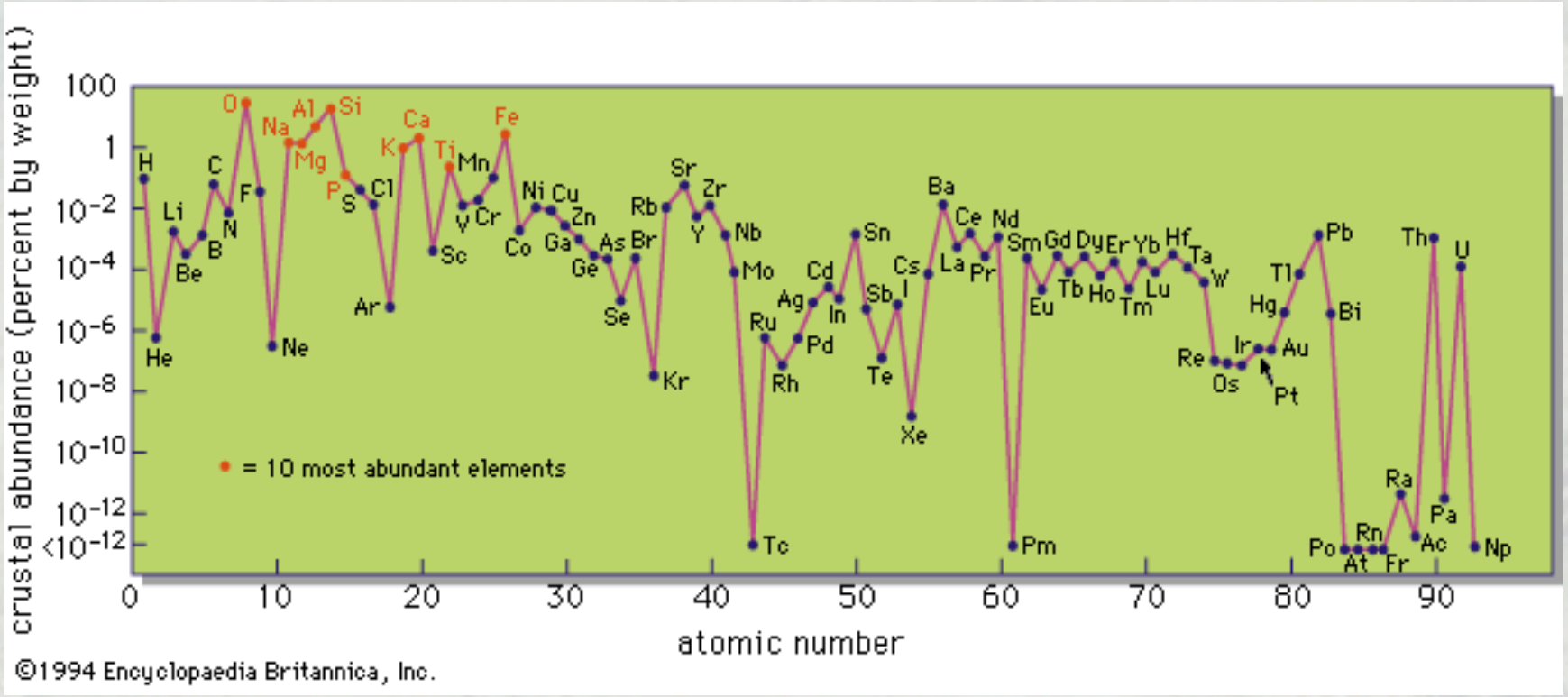


Bardi and Pagani, TOD 2007
http://europe.theoildrum.com/node/3086

Mineral	Peak year (logistic)	URR (tons) from logistic fitting	URR (tons) from USGS: reserves + cumulative production up to 2006
Mercury	1962	$(5.8 \pm 0.4) \cdot 10^5$	$5.9 \cdot 10^5$
Tellurium	1984	$(1.0 \pm 0.4) \cdot 10^4$	$2.8 \cdot 10^4$
Lead	1986	$(3.3 \pm 0.2) \cdot 10^8$	$2.9 \cdot 10^8$
Cadmium	1989	$(1.33 \pm 0.09) \cdot 10^6$	$1.5 \cdot 10^6$
Potash	1989	$(1.54 \pm 0.09) \cdot 10^9$	$9.5 \cdot 10^9$
Phosphate rock	1989	$(8.1 \pm 0.4) \cdot 10^9$	$2.4 \cdot 10^{10}$
Thallium	1995	$(4.7 \pm 0.3) \cdot 10^2$	$7.6 \cdot 10^2$
Selenium	1994	$(1.1 \pm 0.14) \cdot 10^5$	$1.6 \cdot 10^5$
Zirconium minerals concentrates	1994	$(3.9 \pm 0.25) \cdot 10^7$	$6.7 \cdot 10^7$
Rhenium	1998	$(1.0 \pm 0.3) \cdot 10^3$	$3.3 \cdot 10^3$
Gallium	2002	$(2.5 \pm 0.5) \cdot 10^3$	$1.65 \cdot 10^4$ (?)

Bardi and Pagani, TOD 2007
http://europe.theoildrum.com/node/3086

Crustal abundance of the elements



"Common" elements: ~ 0.1- 1% in weight. Fe, Si, Al, Mg, Ti...
"Rare" elements: < 0.01% in weight. Cu, Pb, Zn, Ni, Co .....
"Trace" elements <0.001 in weight. Au, Pt, Ir, Rh, In, Se, Ga.....

Conclusion about conventional mining

1. “Common” : e.g. Fe, Al, Ti, Si, Mg
No problems of scarcity as long as energy is available at current levels

2. “Rare”: e.g. Cu, Sn, Ni, Sb, Ag....
Needs significant increase in energy availability to maintain current production

3. “Traces”: e.g. Pt, In, Se, Ga,....
Would need huge increases in energy availability to maintain current production

- Seawater mining
- Seafloor mining
- Landfill mining
- Urban mining

Substitution?

H.E. Geller and A.M. Weinberg “American Economic Review” 1976

“The **principle of infinite substitutability**: “society can subsist on inexhaustible or near inexhaustible minerals... and would largely be based on glass, plastic, wood, cement, iron, aluminium and magnesium.

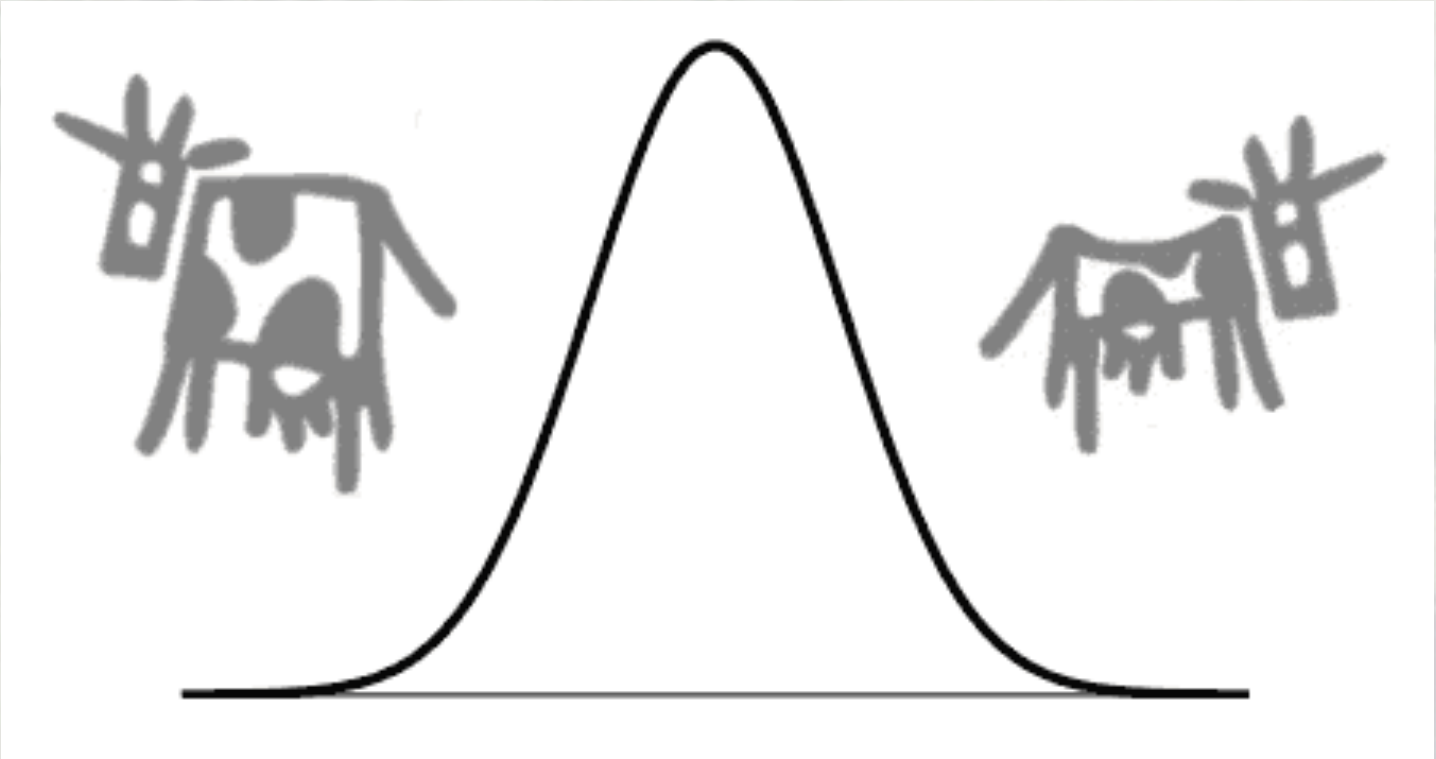
“Energy is the ultimate raw material”

Cu: 50 MJ/kg Al: 210 MJ/kg

Conclusion:
be creative!

Barcelona; 18 October 2008

Conclusion: learn to do more with less



To learn more

U. Bardi: “The universal mining machine” TOD 2008
europe.theoildrum.com/node/3451

U. Bardi and M. Pagani: “Peal Minerals”, TOD 2007,
europe.theoildrum.com/node/3086

U. Bardi: “Mining the Oceans”, TOD 2008,
www.theoildrum.com/node/4558

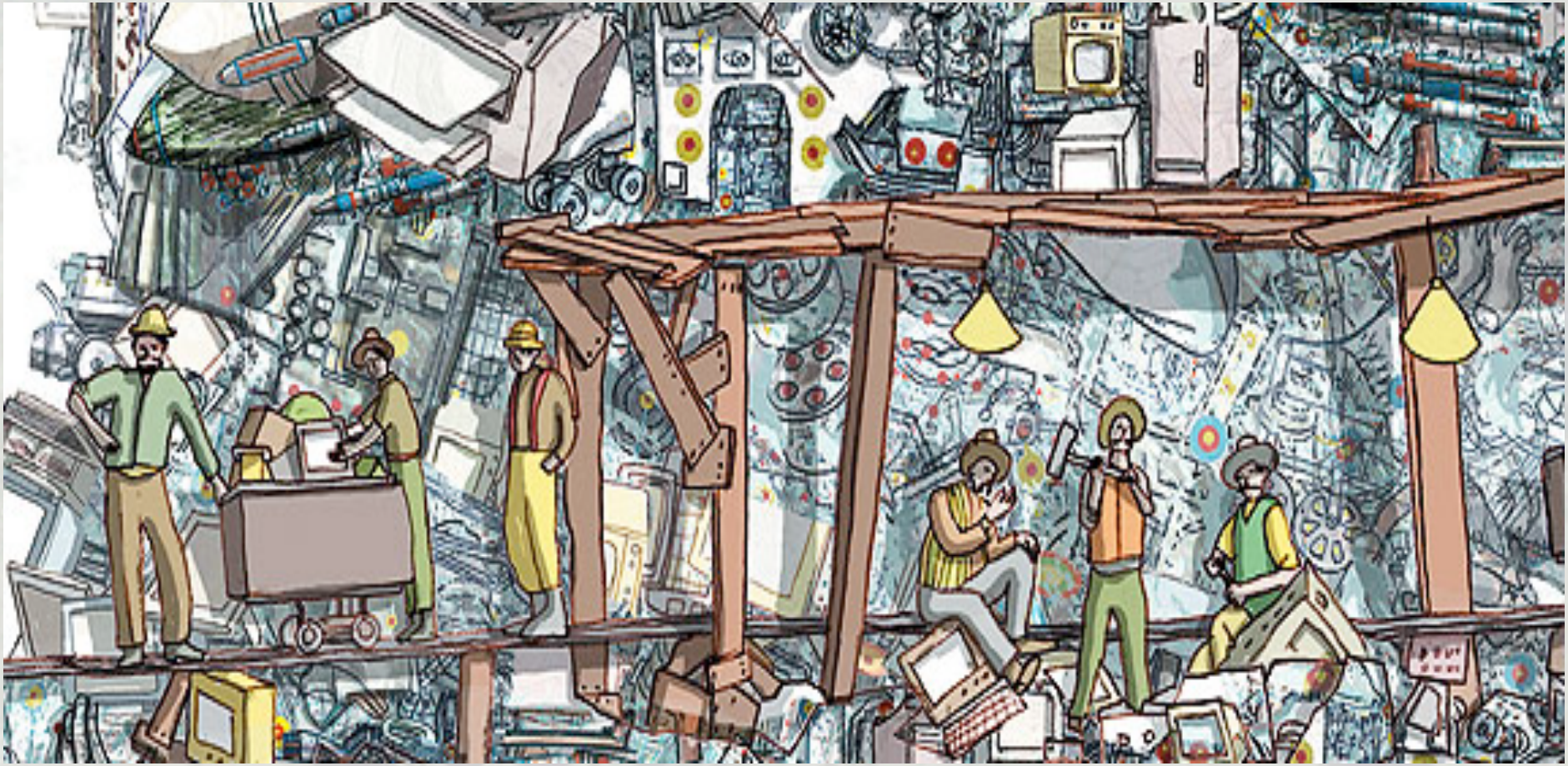
U. Bardi and A. Lavacchi: “Peak Garbage”
Proceedings of the 2008 Wessex conference on waste management, Granada

ASPO ITALIA

The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

FLORENTINA · STVDIORVM · VNIVERSITAS

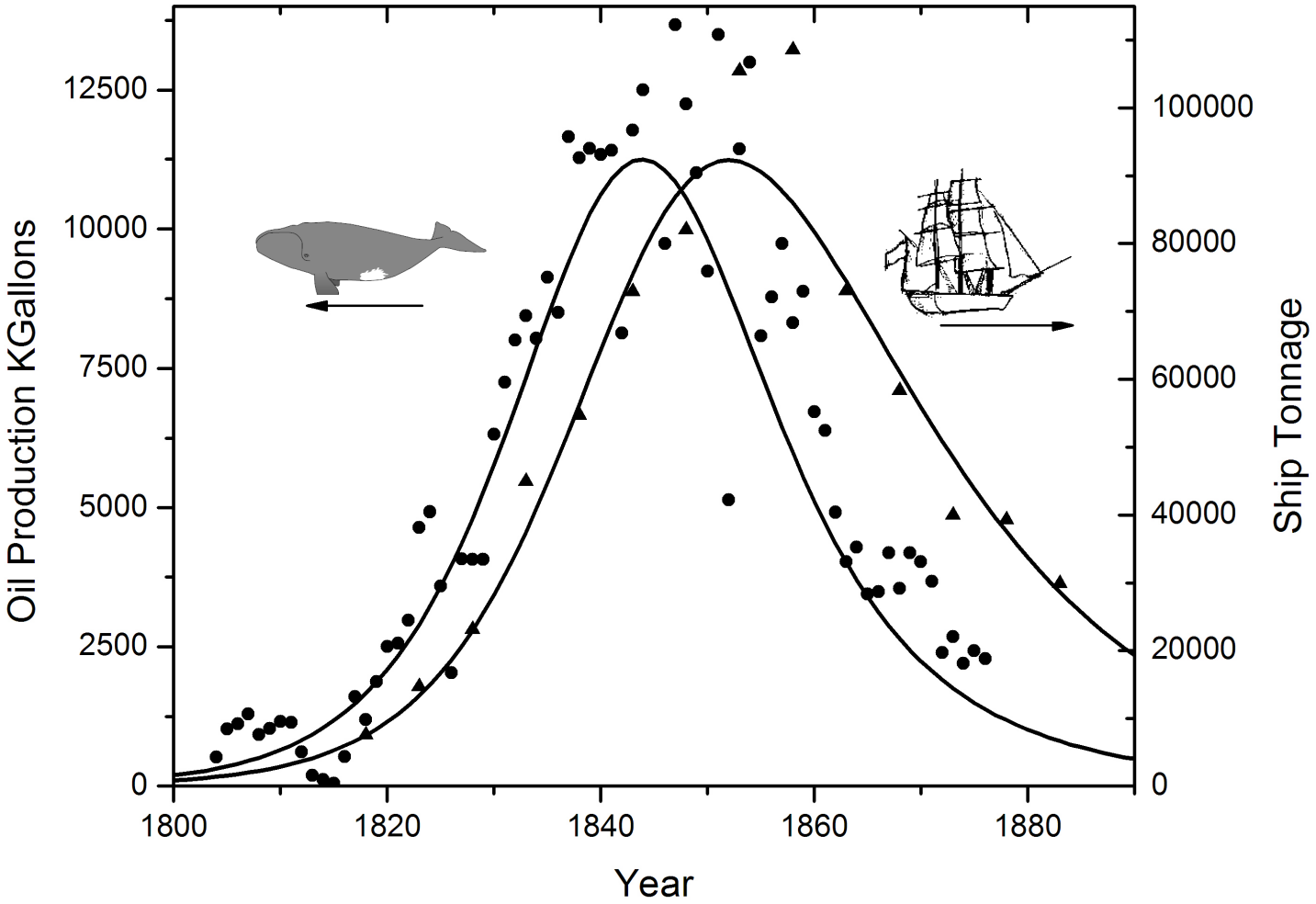
There is gold in them thar smelly hills: Landfill Mining on the rise

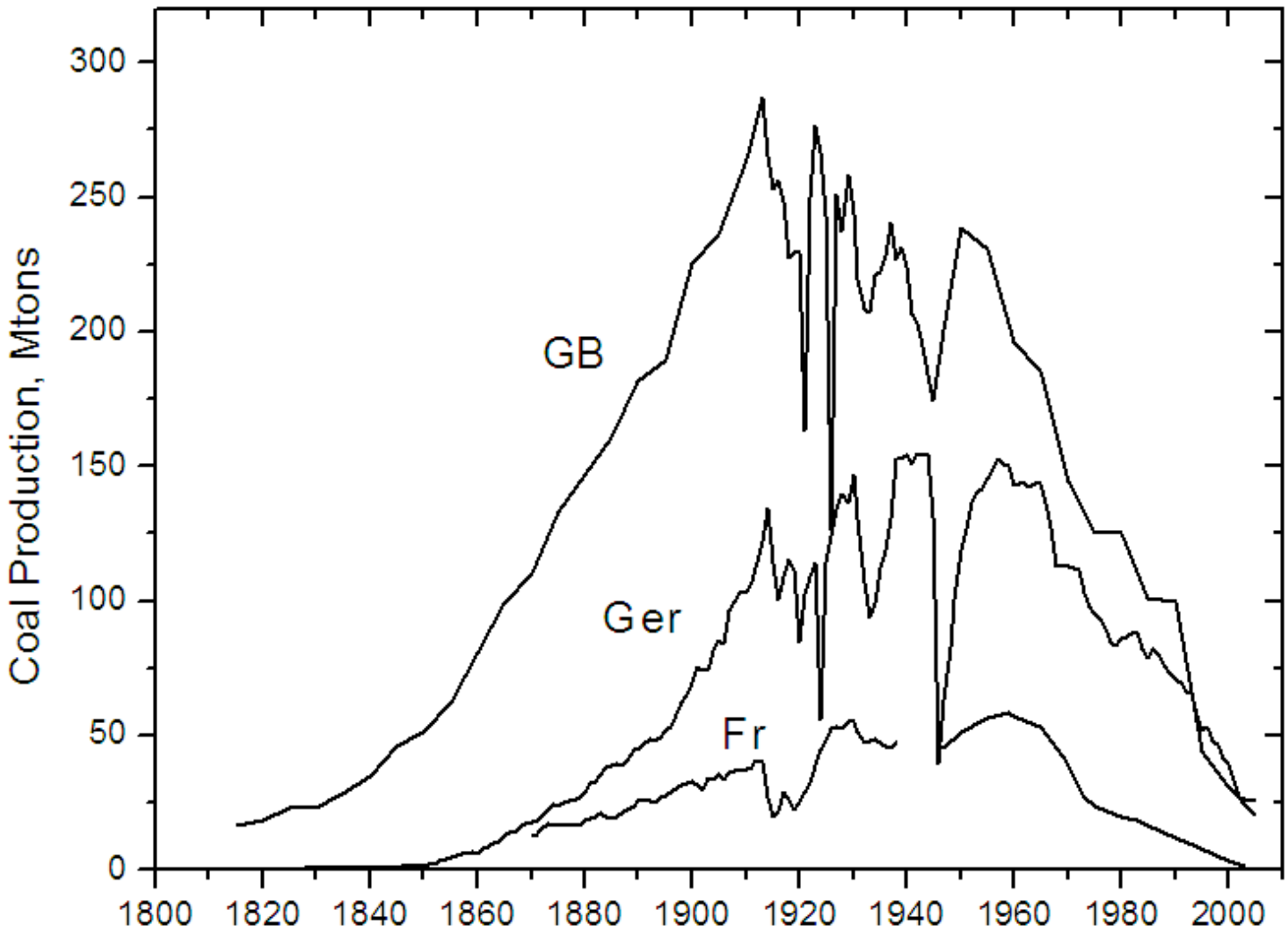


http://www.fastcompany.com/magazine/107/landfill.html

St. Helen Re-mining project; P. Davidson 2008

- Gross metals revenue £1,026,931
- Total operational costs £1,260,436


Oil Production KGallons
Ship Tonnage
Year
0
2500
5000
7500
10000
12500
0
20000
40000
60000
80000
100000
1800
1820
1840
1860
1880

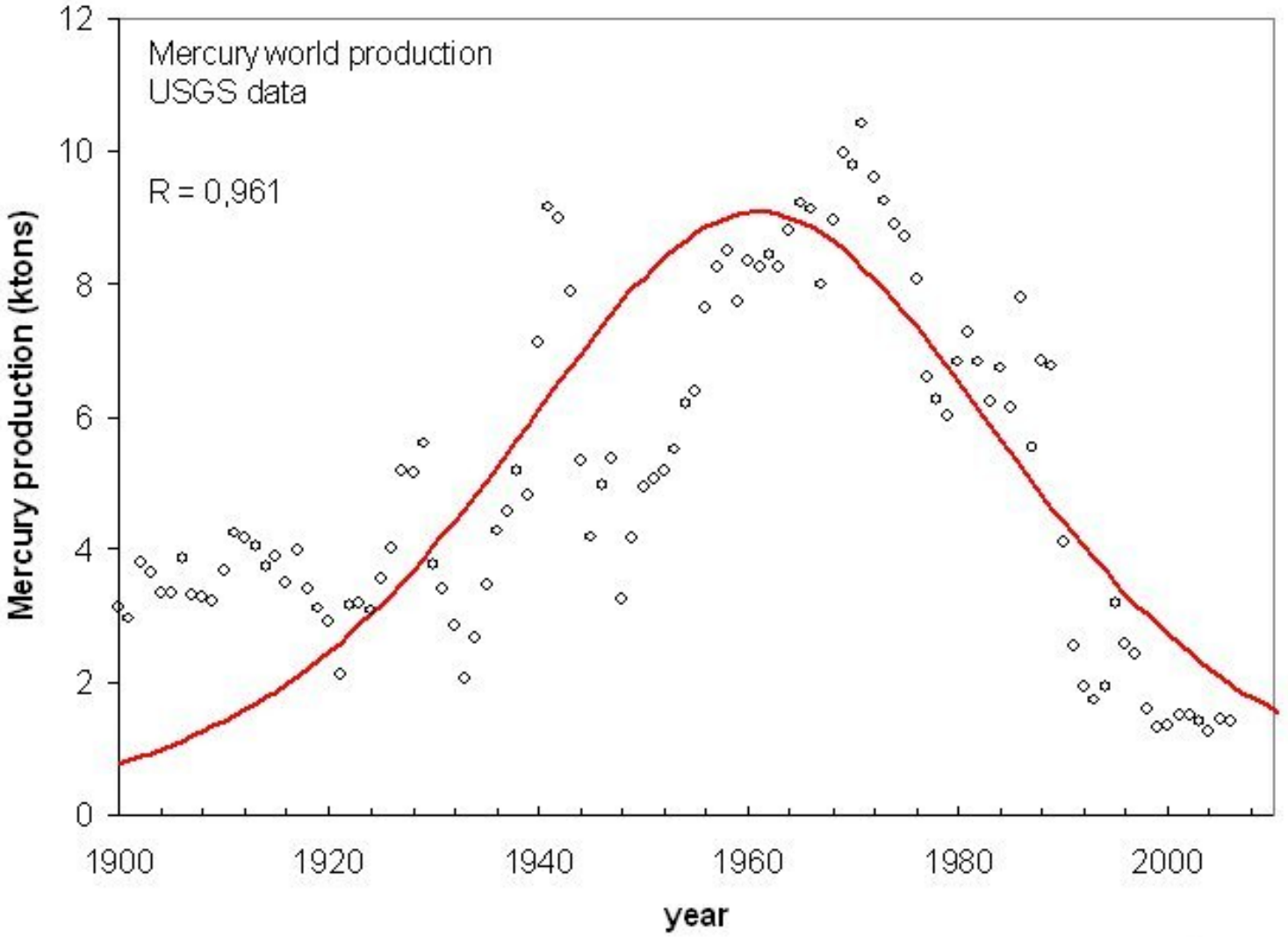


Coal historical production in Europe

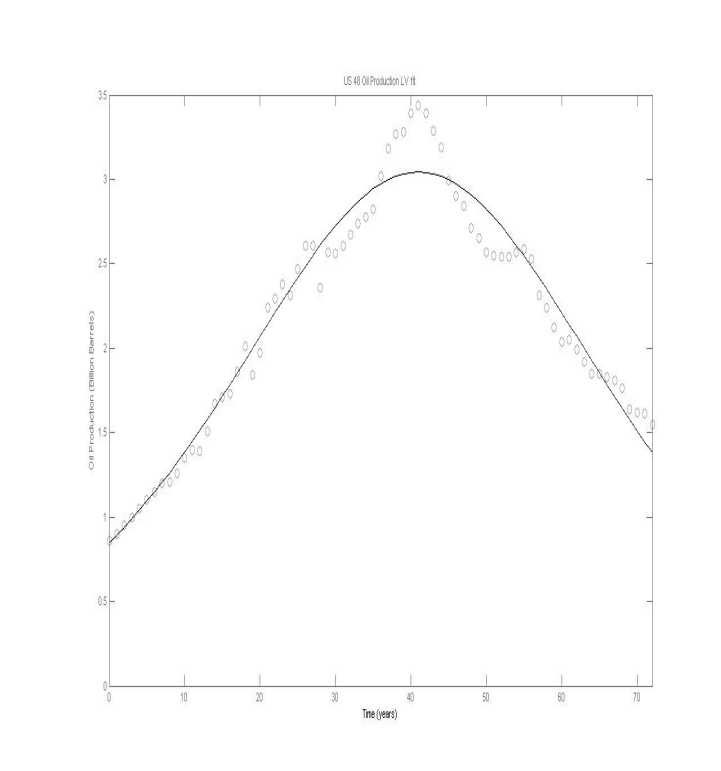
Data from The Coal Authority (GB), BGR (D), Charbonnages de France (Fr)

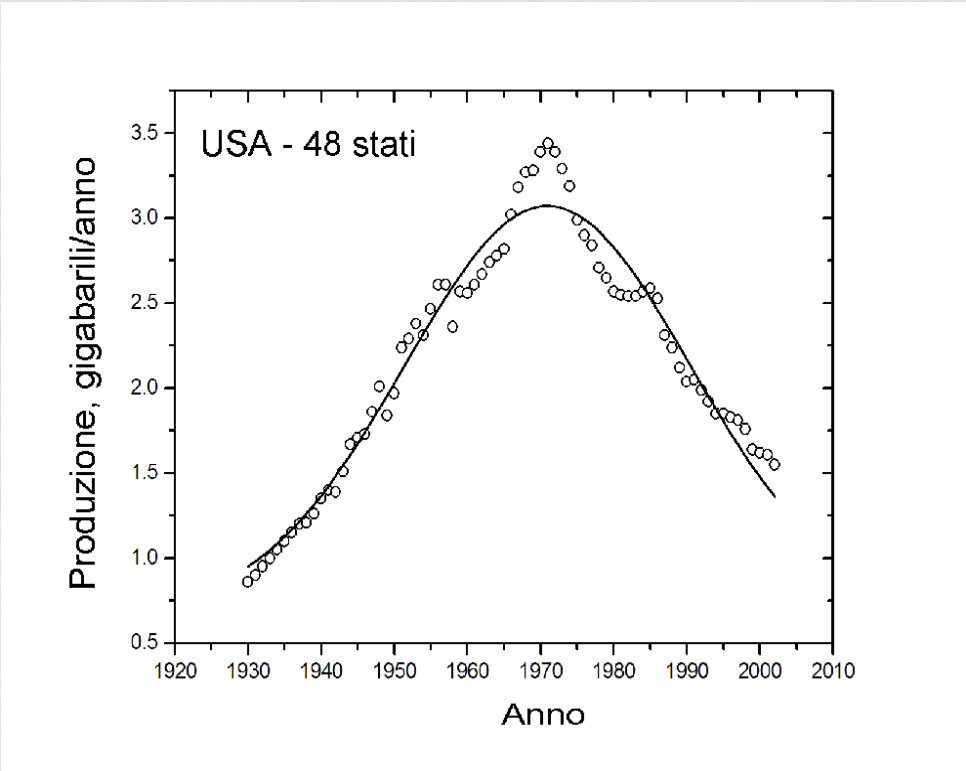
Data from BGR, germany, Japan Coal Institute and Charbonnages de France

European Coal Production



Bardi and Pagani, TOD 2007
http://europe.theoildrum.com/node/3086

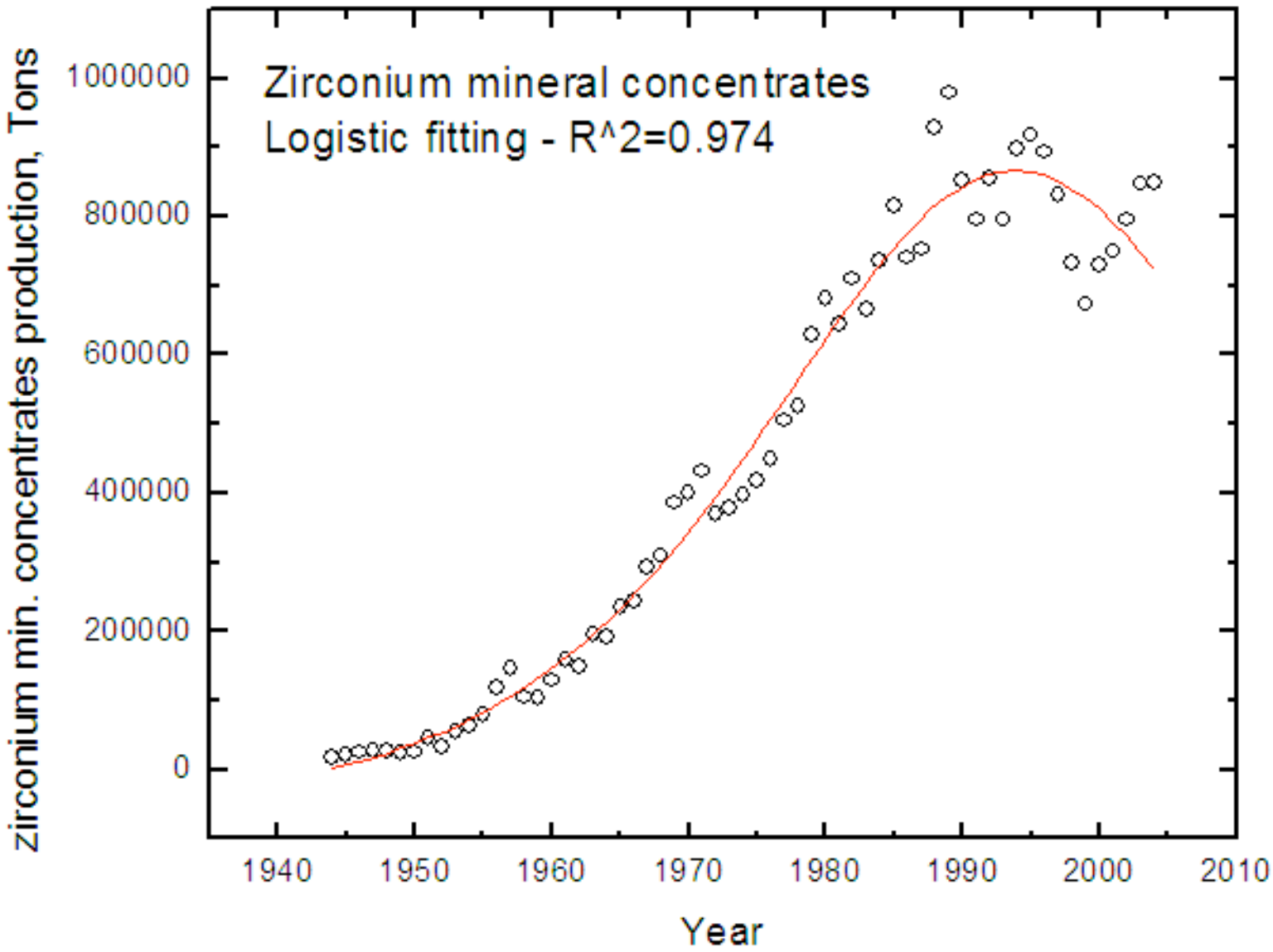




Dynamic model

Logistic model

US 48 oil production – Bardi and Lavacchi 2008



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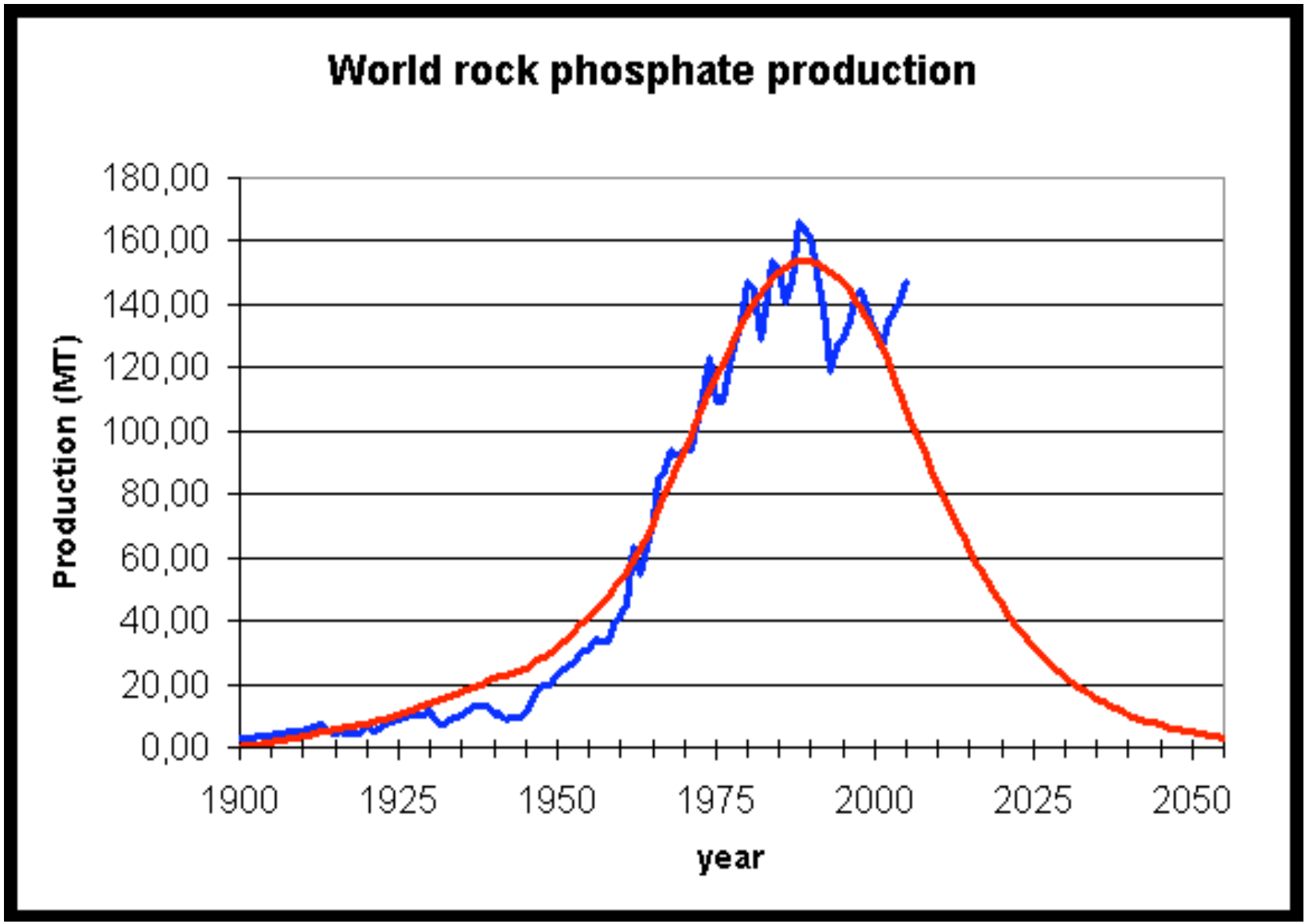

Dery and Anderson, The Oil Drum
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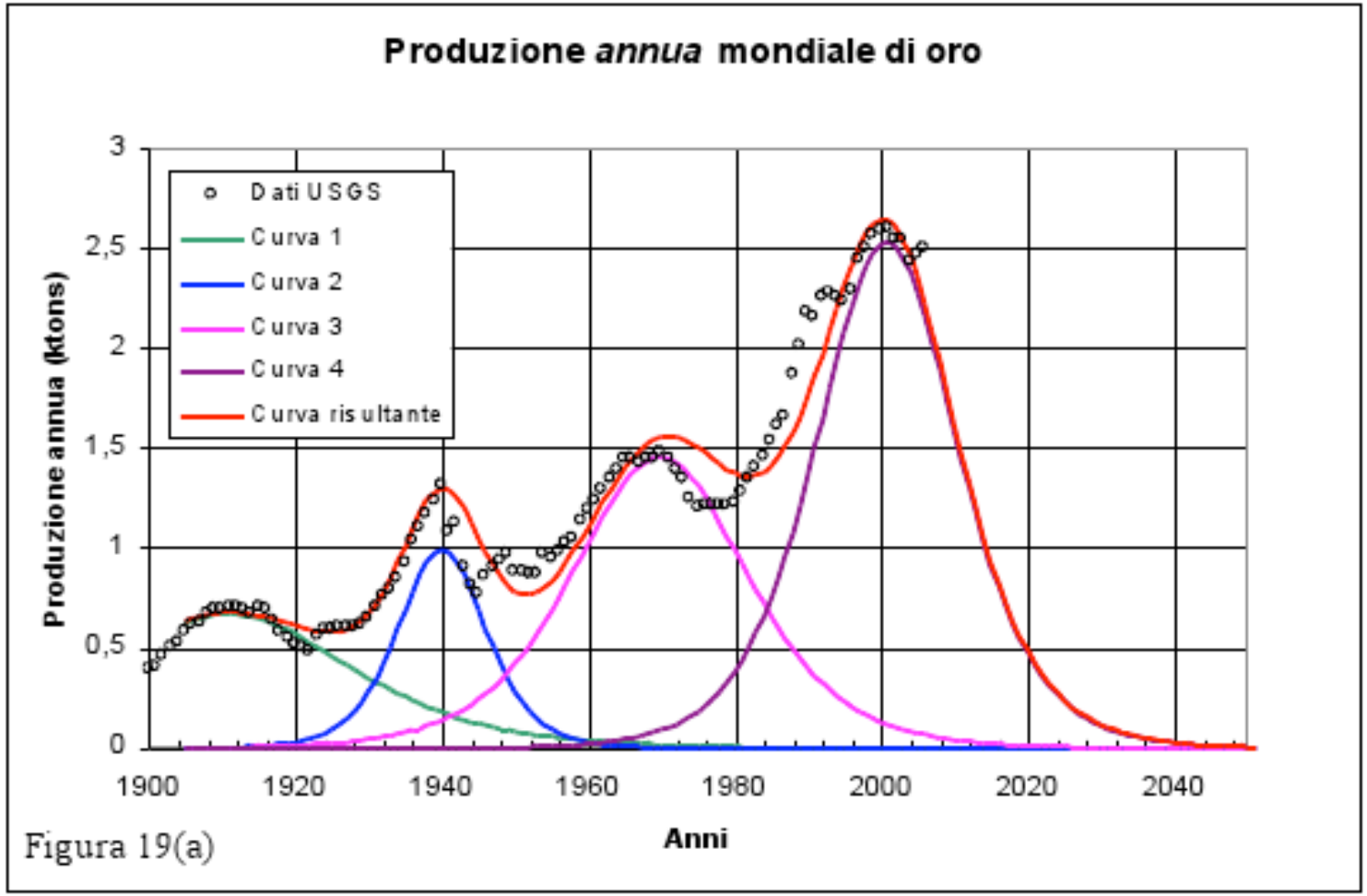
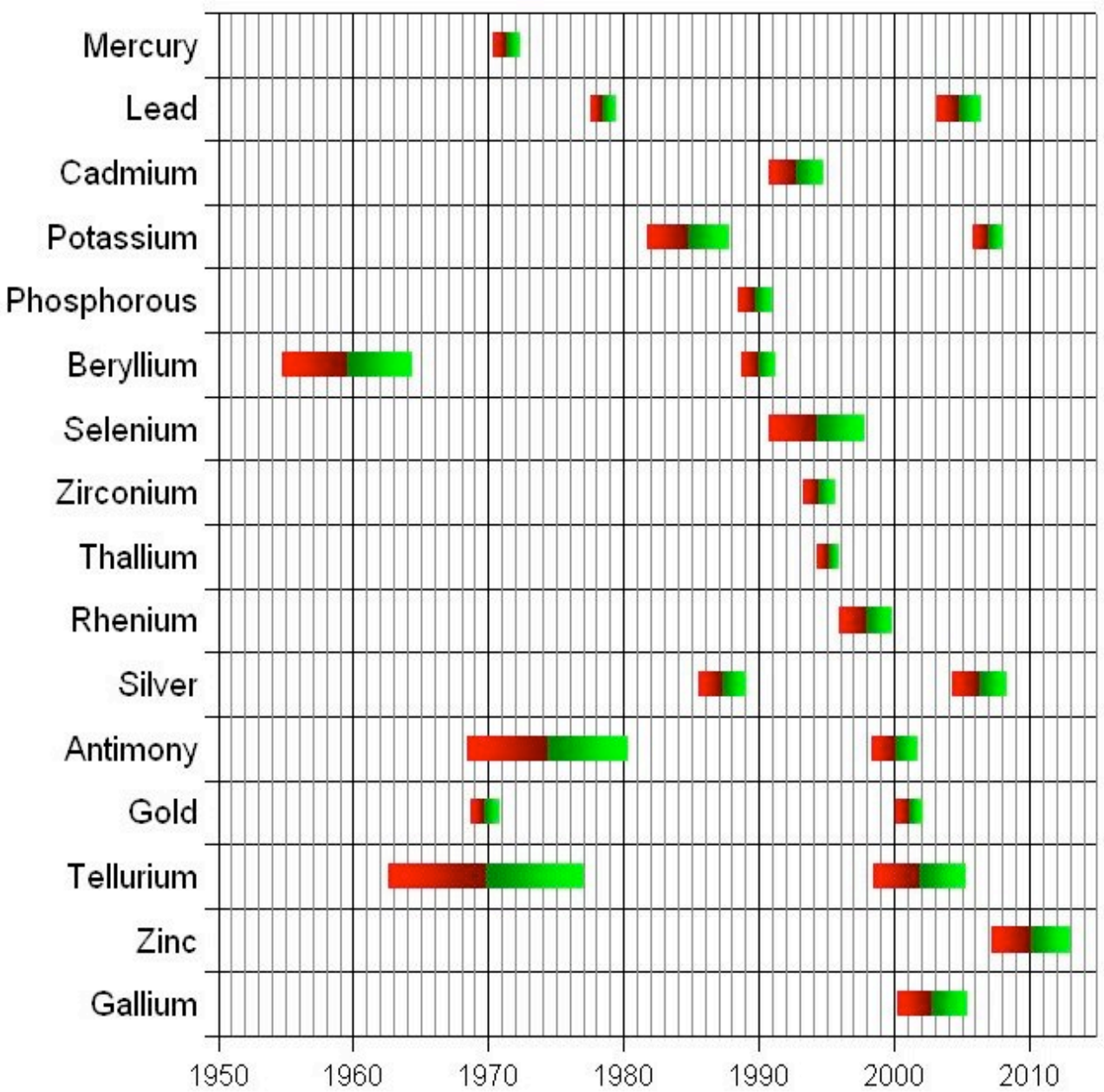

Produzione *annua* mondiale di oro
Dati USGS
Curva 1
Curva 2
Curva 3
Curva 4
Curva risultante
Produzione annua (ktons)
3
2,5
2
1,5
1
0,5
0
1900
1920
1940
1960
1980
2000
2020
2040
Anni

Figura 19(a)

Minerals showing peaks between 1950 and 2010



M. Pagani, 2008

Mining the oceans?

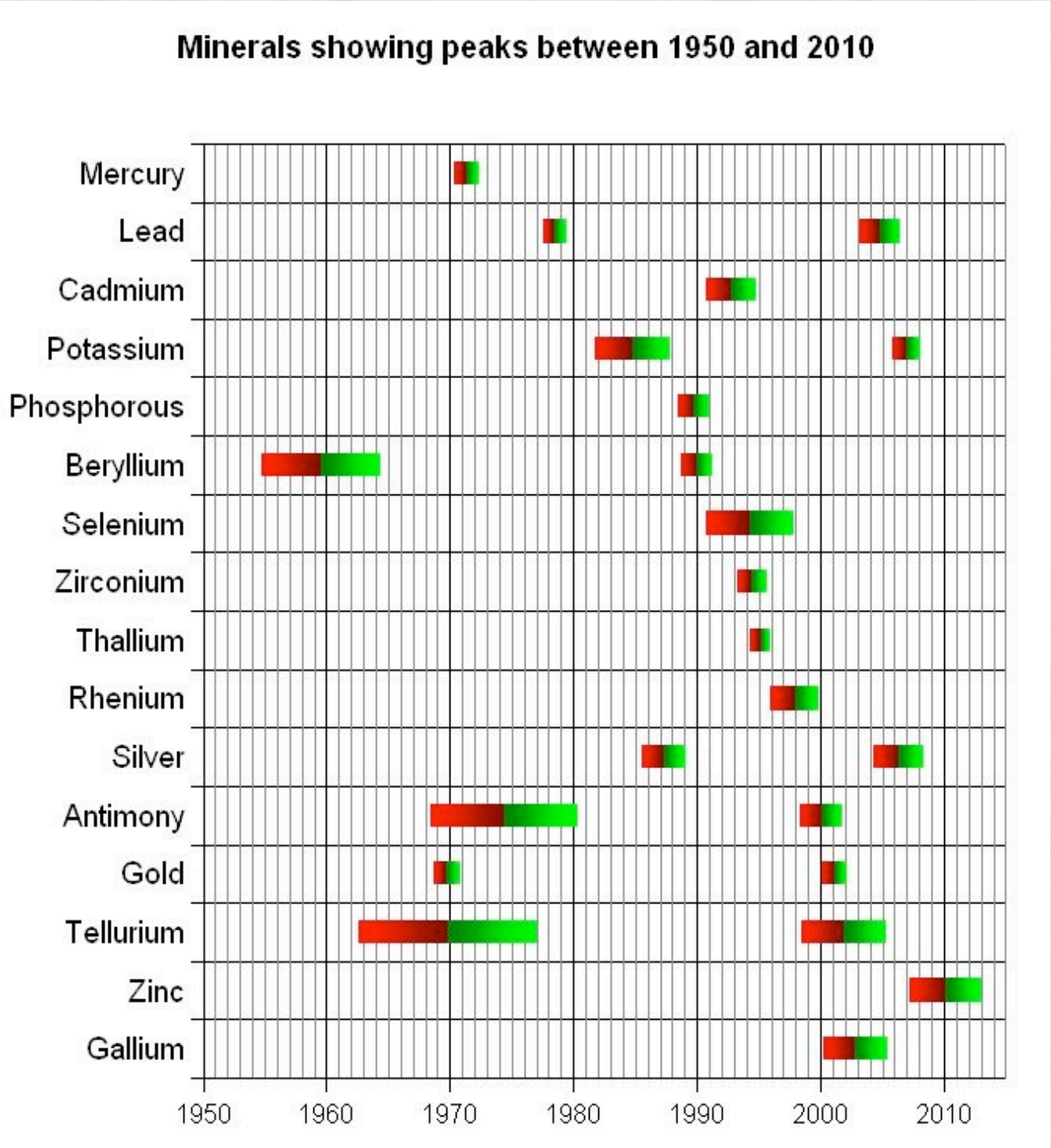
Japan Atomic Energy Institute 1999

Element	Concentration in seawater (ppm)	Total oceanic abundance (tons)	Mineral reserves (tons)
Li	0.178000	2.31E+011	4.10E+006
Ba	0.021000	2.73E+010	1.90E+008
Mo	0.010000	1.30E+010	8.60E+006
Ni	0.006600	8.58E+009	6.70E+007
Zn	0.005000	6.50E+009	1.80E+008
Fe	0.003400	4.42E+009	1.50E+011
U	0.003300	4.29E+009	2.60E+006
V	0.001900	2.47E+009	1.30E+007
Ti	0.001000	1.30E+009	7.30E+008
Al	0.001000	1.30E+009	2.50E+010
Cu	0.000900	1.17E+009	4.90E+008
Mn	0.000400	5.20E+008	4.60E+008
Co	0.000390	5.07E+008	7.00E+009
Sn	0.000280	3.64E+008	6.10E+006
Cr	0.000200	2.60E+008	4.75E+008
Cd	0.000110	1.43E+008	4.90E+005
Pb	0.000030	3.90E+007	7.90E+007
Au	0.000011	1.43E+007	4.20E+004

Element	Total mass in oceans (tons)	Production in 2007 (tons)	Mass of water to be processed (tons)
Li	2.31E+011	2.50E+004	1.40E+011
Mo	1.30E+010	1.87E+005	1.87E+013
U	4.29E+009	6.65E+004	2.02E+013
V	2.47E+009	5.86E+004	3.08E+013
Cd	1.43E+008	1.99E+004	1.81E+014
Au	1.43E+007	2.50E+003	2.27E+014
Sn	3.64E+008	3.00E+005	1.07E+015
Ni	8.23E+008	1.78E+006	2.81E+015
Cu	1.17E+009	1.56E+007	1.73E+016
Mn	5.20E+008	1.16E+007	2.90E+016
Zn	6.50E+009	1.80E+008	3.60E+016
Al	1.30E+009	3.80E+007	3.80E+016
Cr	2.60E+008	2.00E+007	1.00E+017
Pb	3.90E+007	3.55E+006	1.18E+017
Fe	4.42E+009	2.26E+009	6.65E+017
Ti	1.17E+006	6.10E+006	6.78E+018
Co	8.84E+006	6.23E+007	9.16E+018

Total mass of the oceans: 1.4 E+18 tons

Total volume of water desalinated today:1.6 E+10 tons


Minerals showing peaks between 1950 and 2010
Mercury
Lead
Cadmium
Potassium
Phosphorous
Beryllium
Selenium
Zirconium
Thallium
Rhenium
Silver
Antimony
Gold
Tellurium
Zinc
Gallium
1950
1960
1970
1980
1990
2000
2010

ATLANTROPA

1 *“Sverdrup”* = 1 E+6 tons/s
= 3 E+13 tons/year

Strait of Gibraltar = 1 Sverdrup

It contains a mass of uranium equivalent to today's yearly production

- Conventional mining is increasingly energy expensive.
- Mining seawater is a hugely expensive task, most likely impossible
- Mining landfills is an extremely complex task and it requires technologies not yet available
- Mining the asteroids is only for science fiction
- Recycling over some levels is also too energy intensive to be practical

Conclusion: try to do more with less

Energy commodities production

By Ugo Bardi
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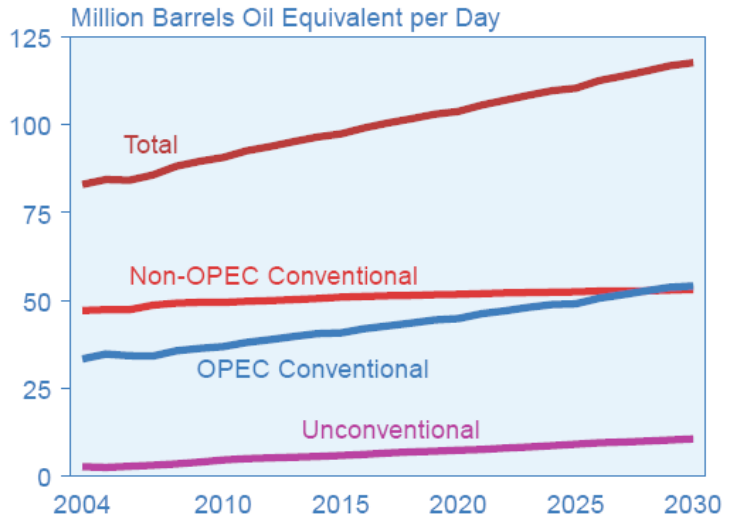
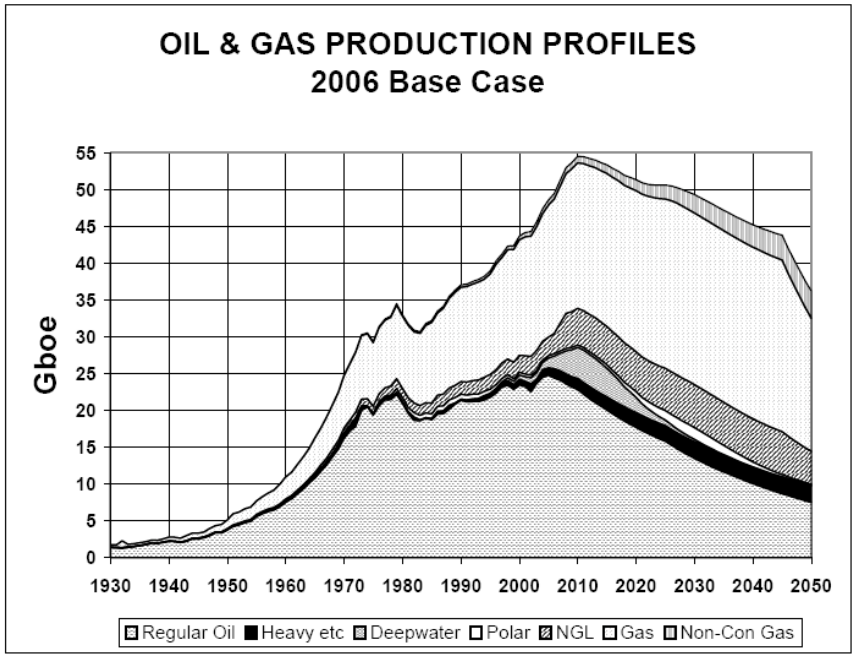
Università di Firenze, Italy
ugo.bardi@unifi.it

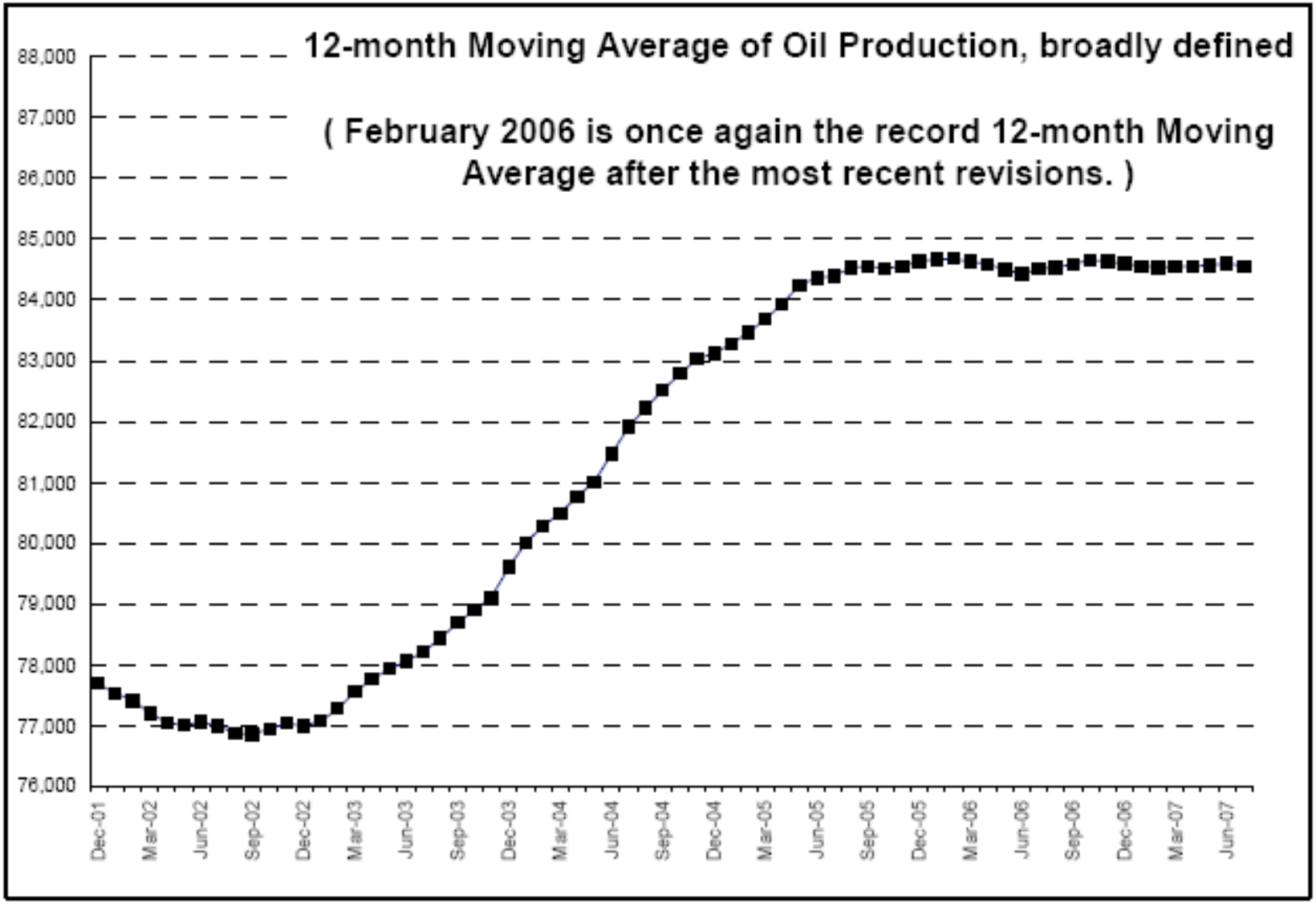
Figure 5. World Liquids Production, 2004-2030



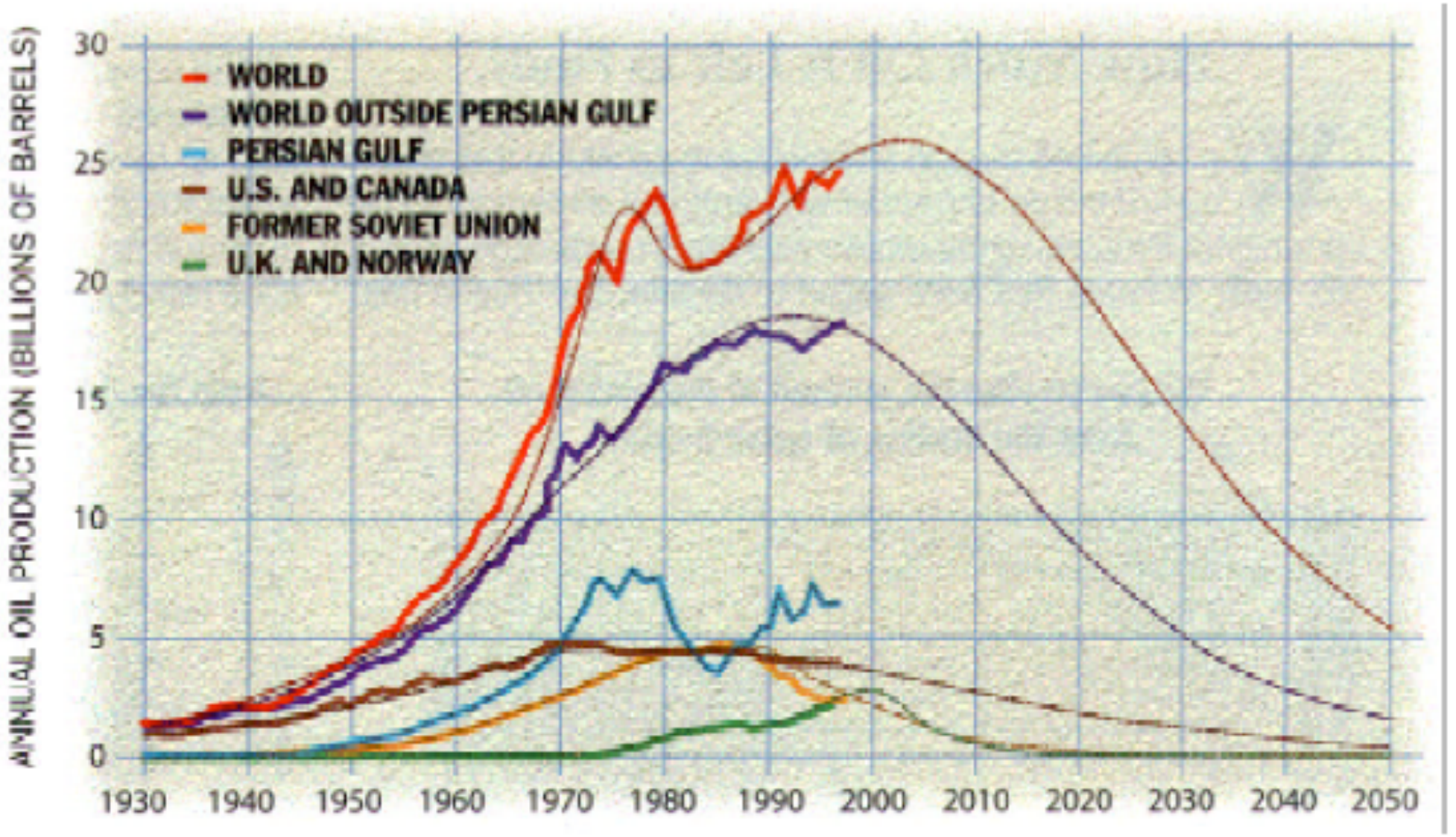
Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).

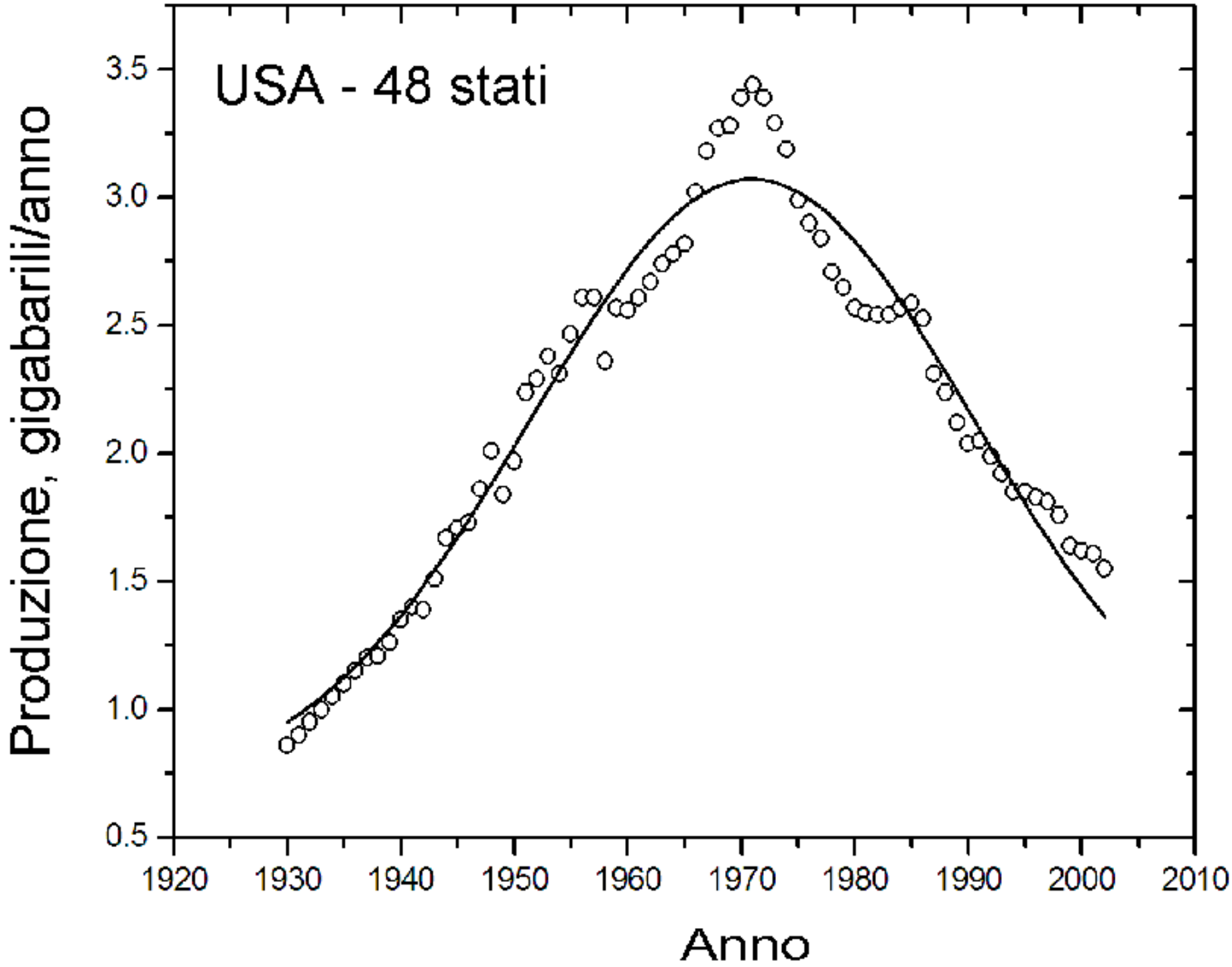


ASPO data Oct 2007

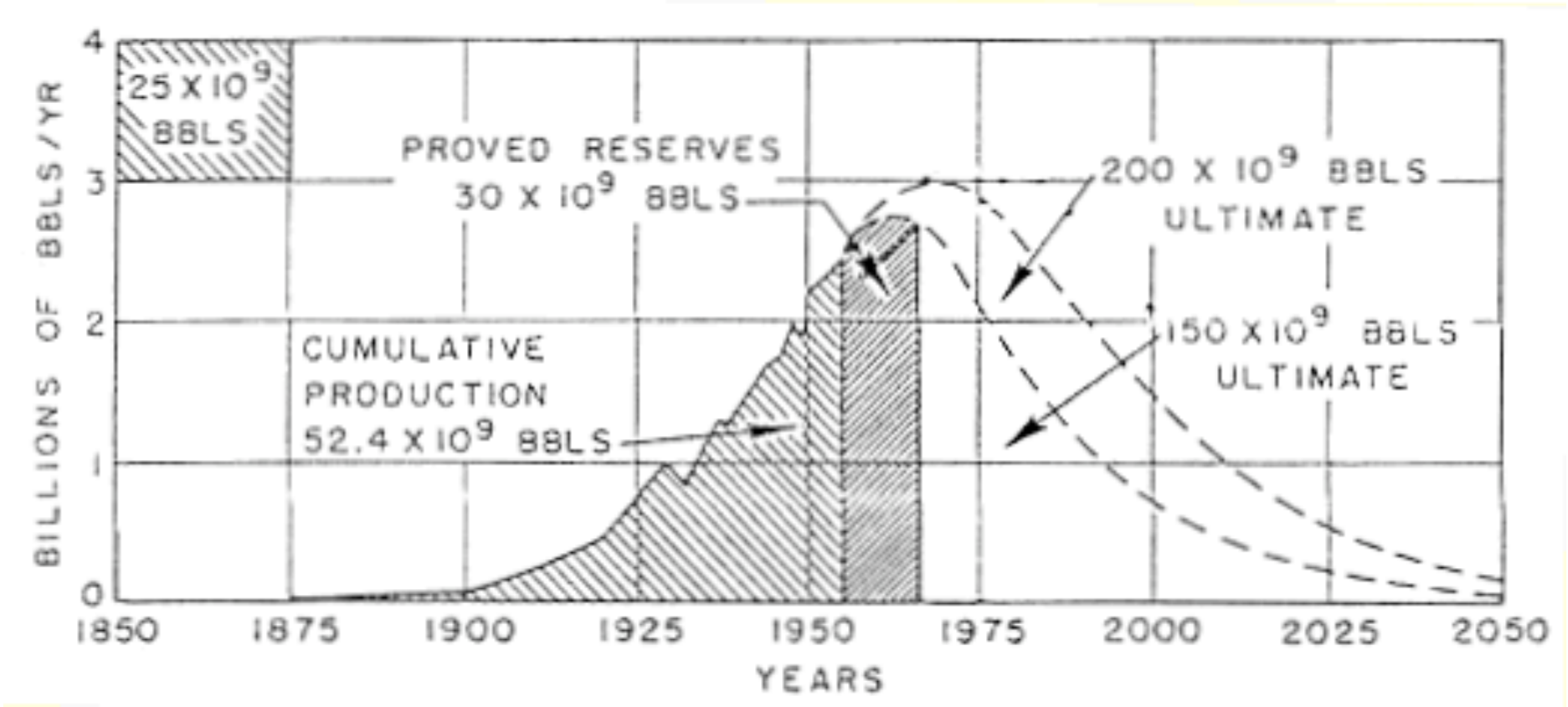


C. Campbell and J. Laherrere – Scientifc American, November 1998




USA - 48 stati
Produzione, gigabarili/anno
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Anno

The Hubbert Model - 1956



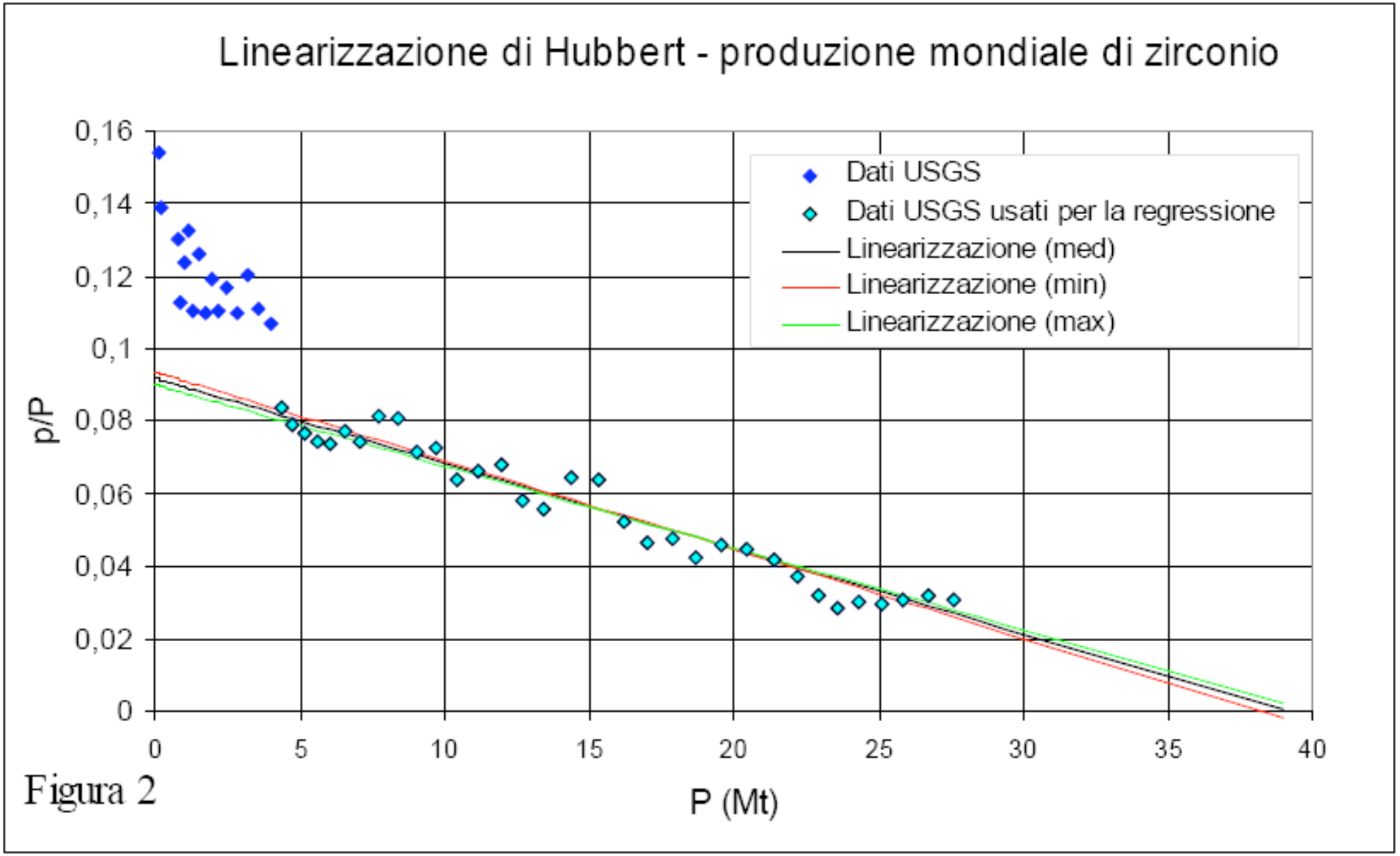
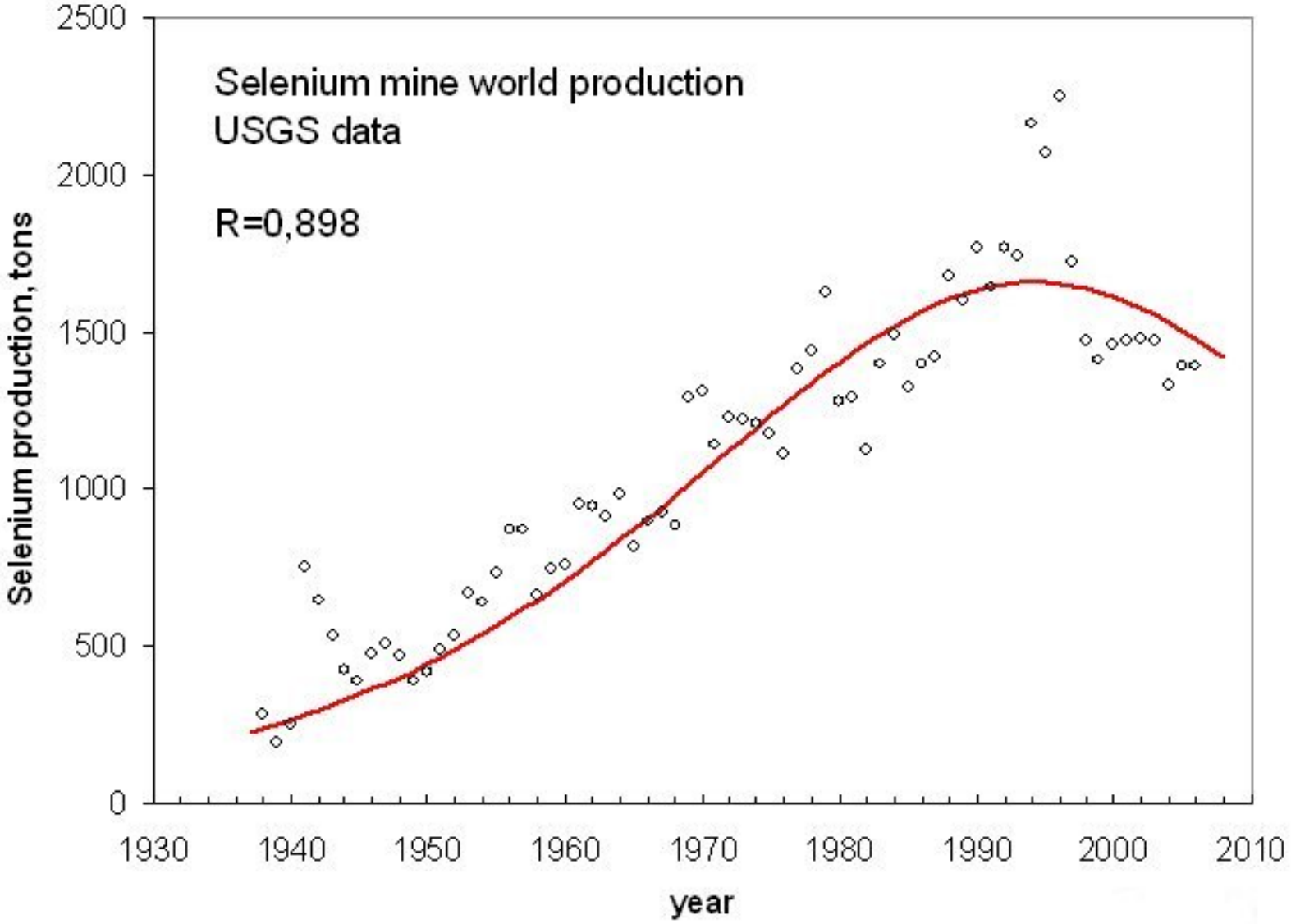
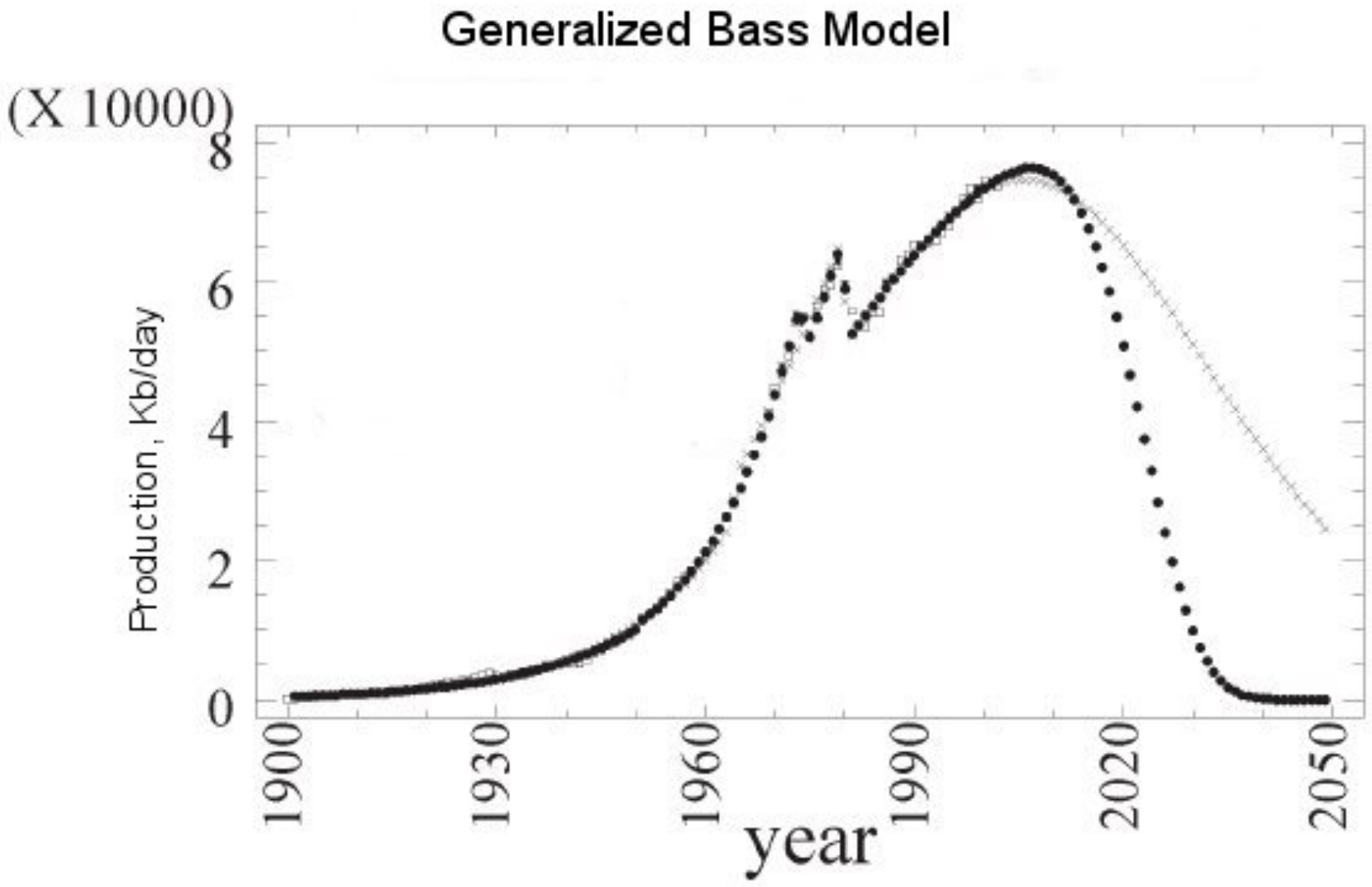

Linearizzazione di Hubbert - produzione mondiale di zirconio
Dati USGS
Dati USGS usati per la regressione
Linearizzazione (med)
Linearizzazione (min)
Linearizzazione (max)
p/P
P (Mt)
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
0
5
10
15
20
25
30
35
40

Figura 2


Selenium mine world production
USGS data
R=0,898
Selenium production, tons
2500
2000
1500
1000
500
0
1930
1940
1950
1960
1970
1980
1990
2000
2010
year

Oil Production, from Guseo et al. (2002)



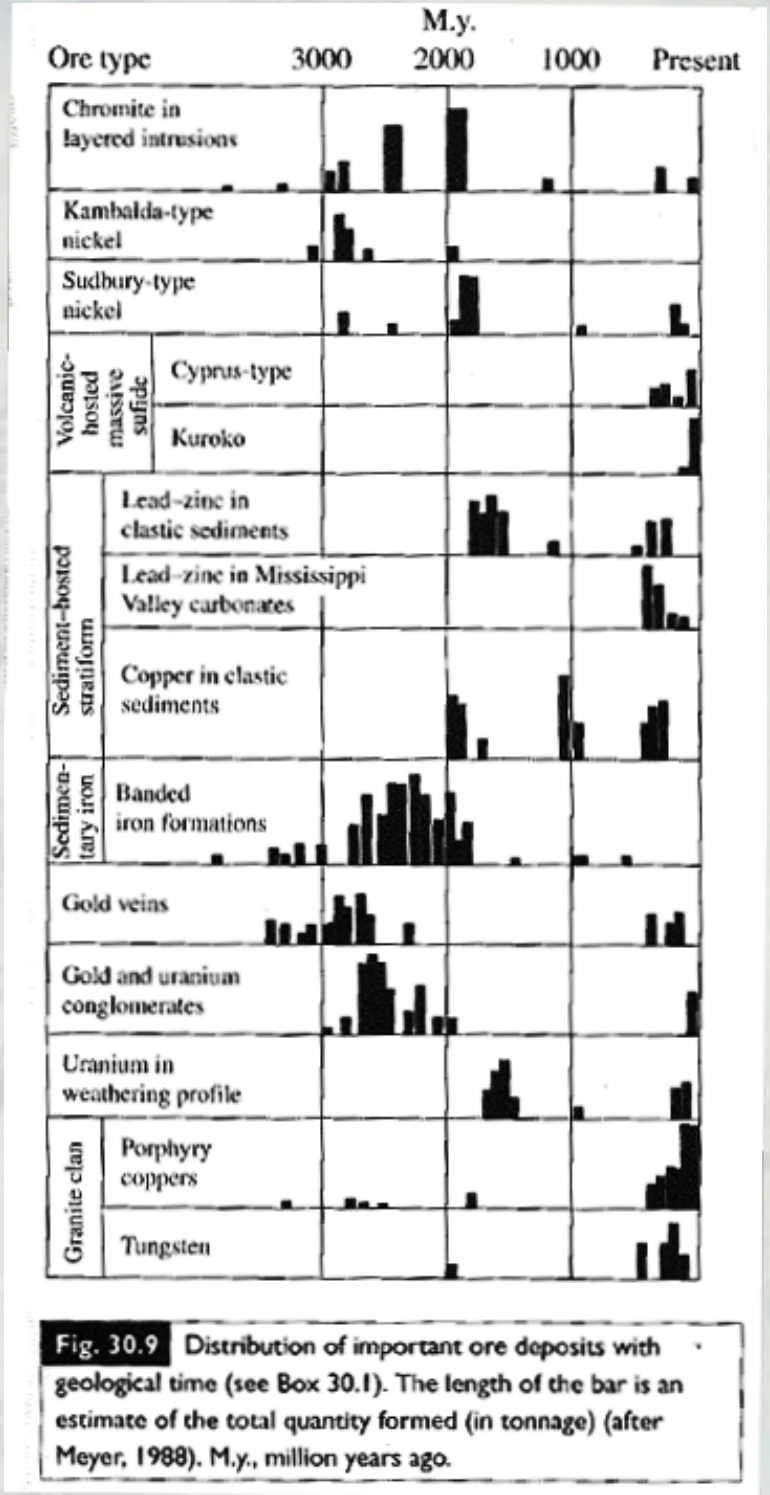
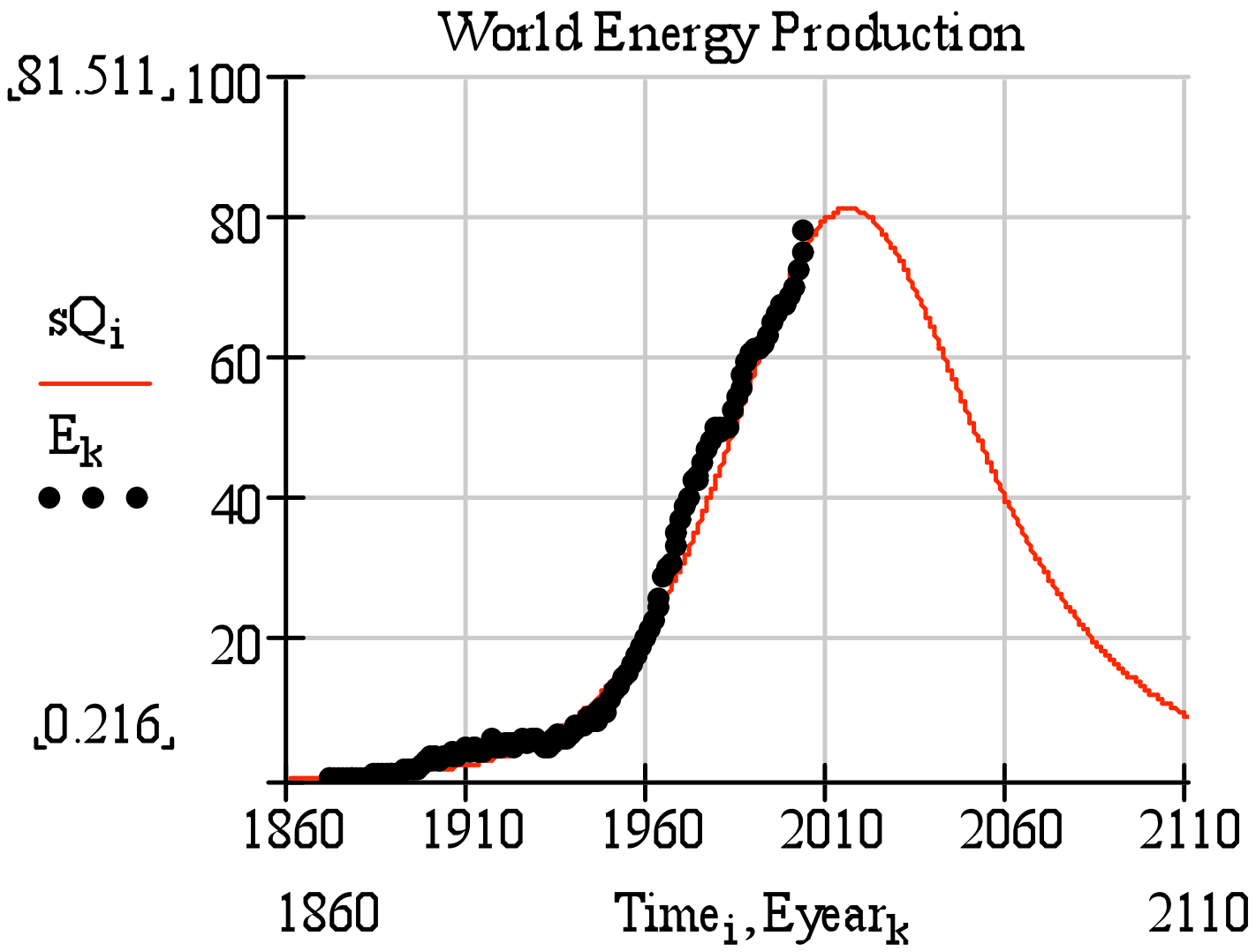


Fig. 30.9 Distribution of important ore deposits with geological time (see Box 30.1). The length of the bar is an estimate of the total quantity formed (in tonnage) (after Meyer, 1988). M.y., million years ago.

From Wenk and Bulakh, 2004

World Energy Production, LV model



The Hirsch approximation (2005)

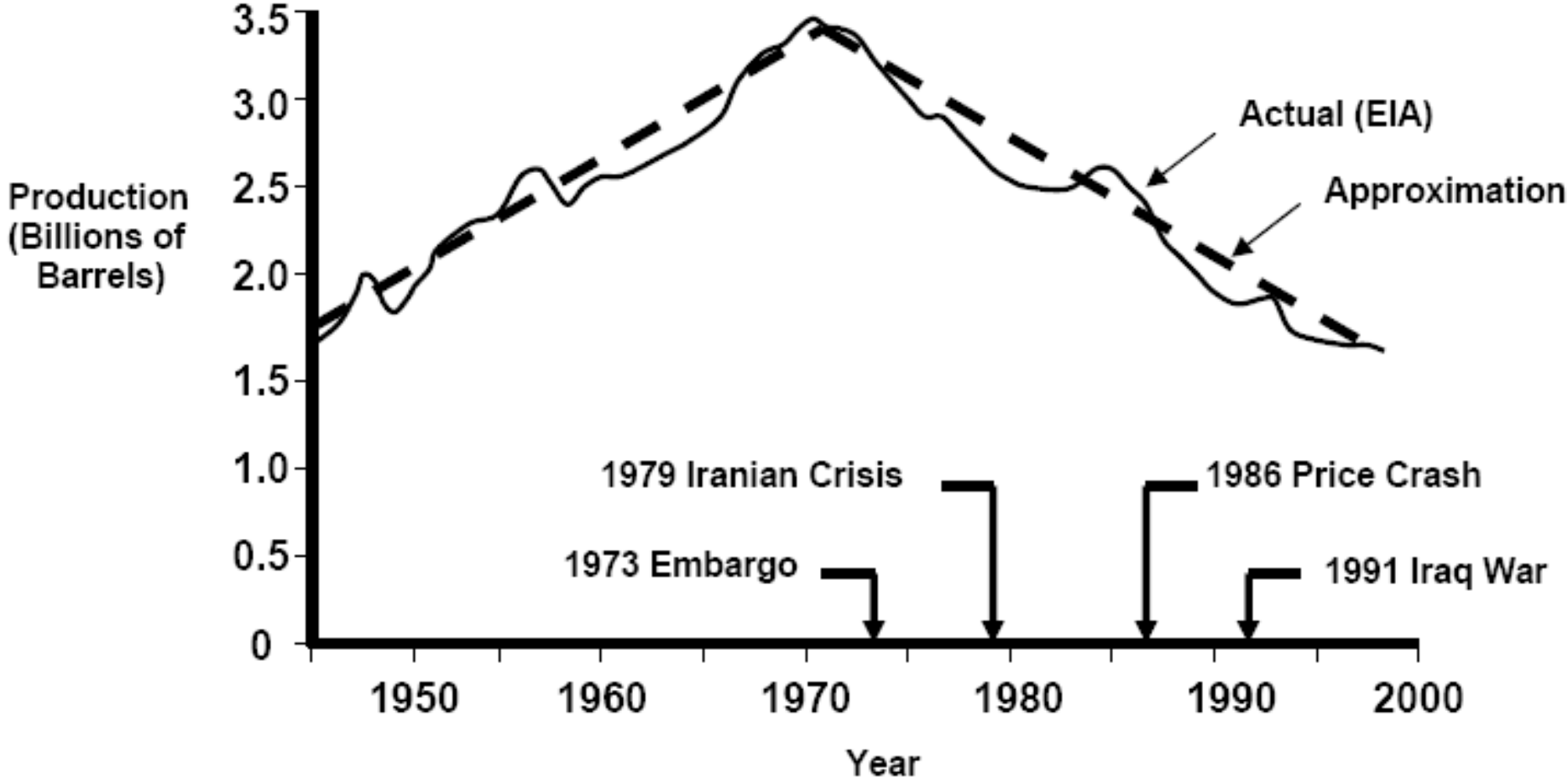
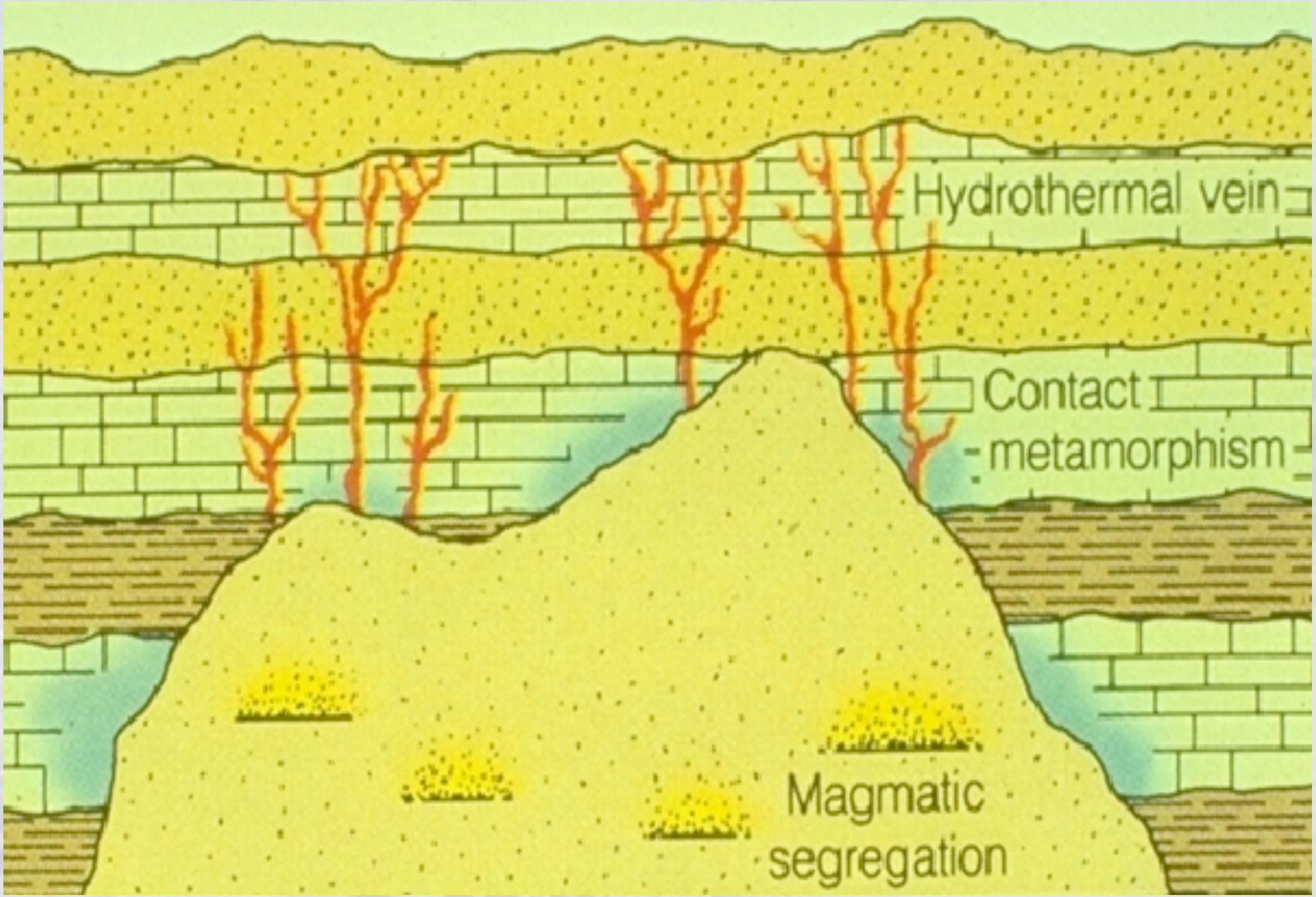
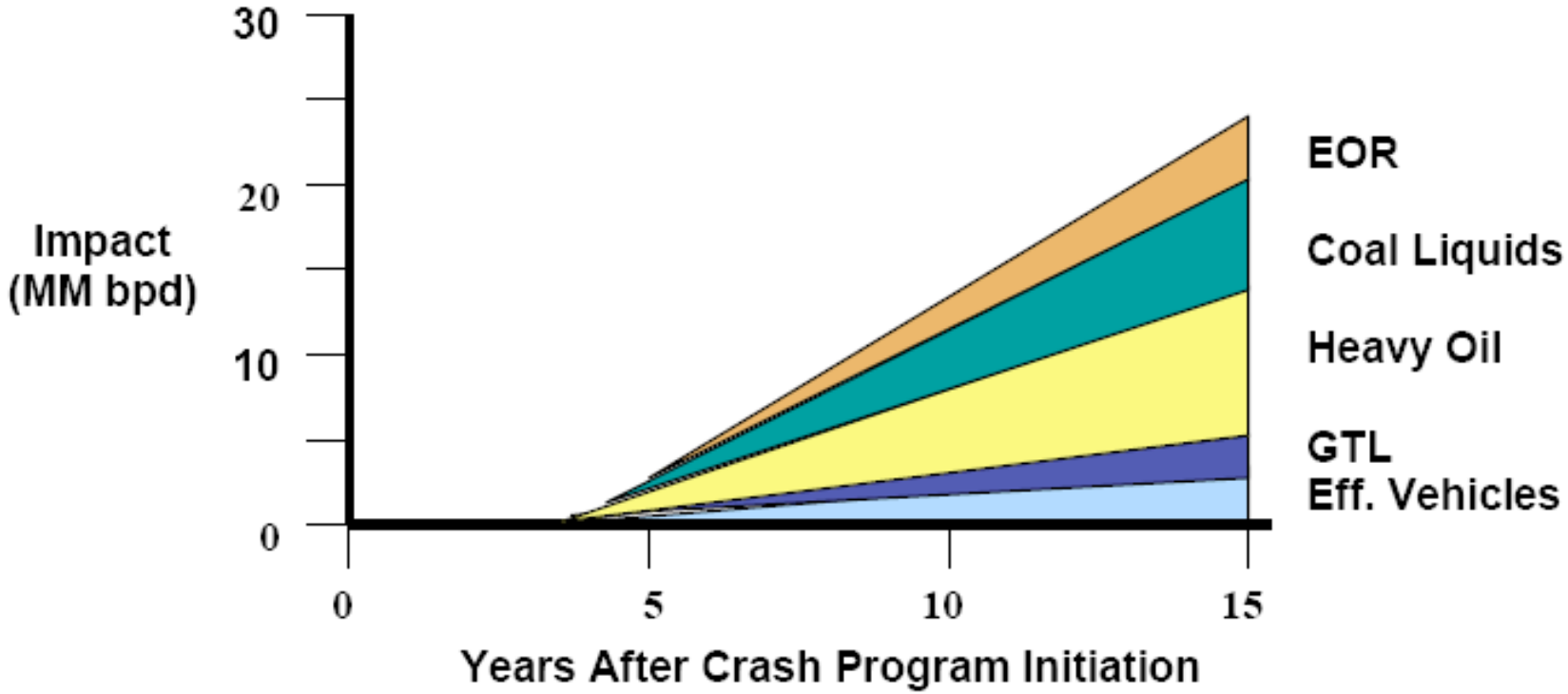


Figure II-2. U.S. Lower 48 Oil Production, 1945-2000



Formation of copper deposits

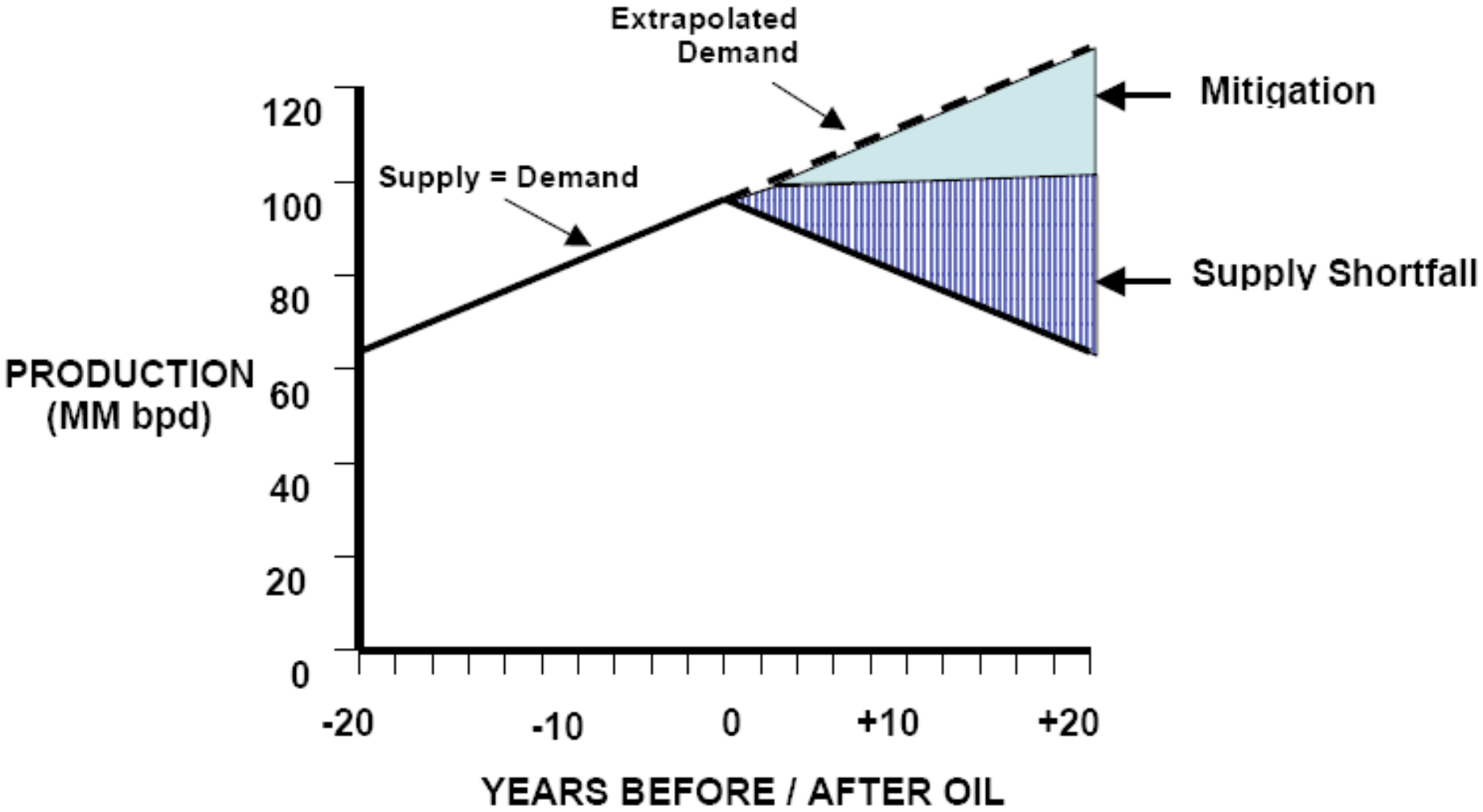
Hirsch 2005


30
20
10
0
Impact
(MM bpd)
0
5
10
15
Years After Crash Program Initiation
EOR
Coal Liquids
Heavy Oil
GTL
Eff. Vehicles

Peaking trends

Mineral	Peak year (logistic)	URR (tons) from logistic fitting	URR (tons) from USGS: reserves + cumulative production up to 2006
Mercury	1962	$(5.8 \pm 0.4) \cdot 10^5$	$5.9 \cdot 10^5$
Tellurium	1984	$(1.0 \pm 0.4) \cdot 10^4$	$2.8 \cdot 10^4$
Lead	1986	$(3.3 \pm 0.2) \cdot 10^8$	$2.9 \cdot 10^8$
Cadmium	1989	$(1.33 \pm 0.09) \cdot 10^6$	$1.5 \cdot 10^6$
Potash	1989	$(1.54 \pm 0.09) \cdot 10^9$	$9.5 \cdot 10^9$
Phosphate rock	1989	$(8.1 \pm 0.4) \cdot 10^9$	$2.4 \cdot 10^{10}$
Thallium	1995	$(4.7 \pm 0.3) \cdot 10^2$	$7.6 \cdot 10^2$
Selenium	1994	$(1.1 \pm 0.14) \cdot 10^5$	$1.6 \cdot 10^5$
Zirconium minerals concentrates	1994	$(3.9 \pm 0.25) \cdot 10^7$	$6.7 \cdot 10^7$
Rhenium	1998	$(1.0 \pm 0.3) \cdot 10^3$	$3.3 \cdot 10^3$
Gallium	2002	$(2.5 \pm 0.5) \cdot 10^3$	$1.65 \cdot 10^4$ (?)

Hirsch 2005


Extrapolated
Demand
Mitigation
Supply = Demand
Supply Shortfall
120
100
80
60
40
20
0
PRODUCTION
(MM bpd)
-20
-10
0
+10
+20
YEARS BEFORE / AFTER OIL

Oil at Another Record, Surging Above $95

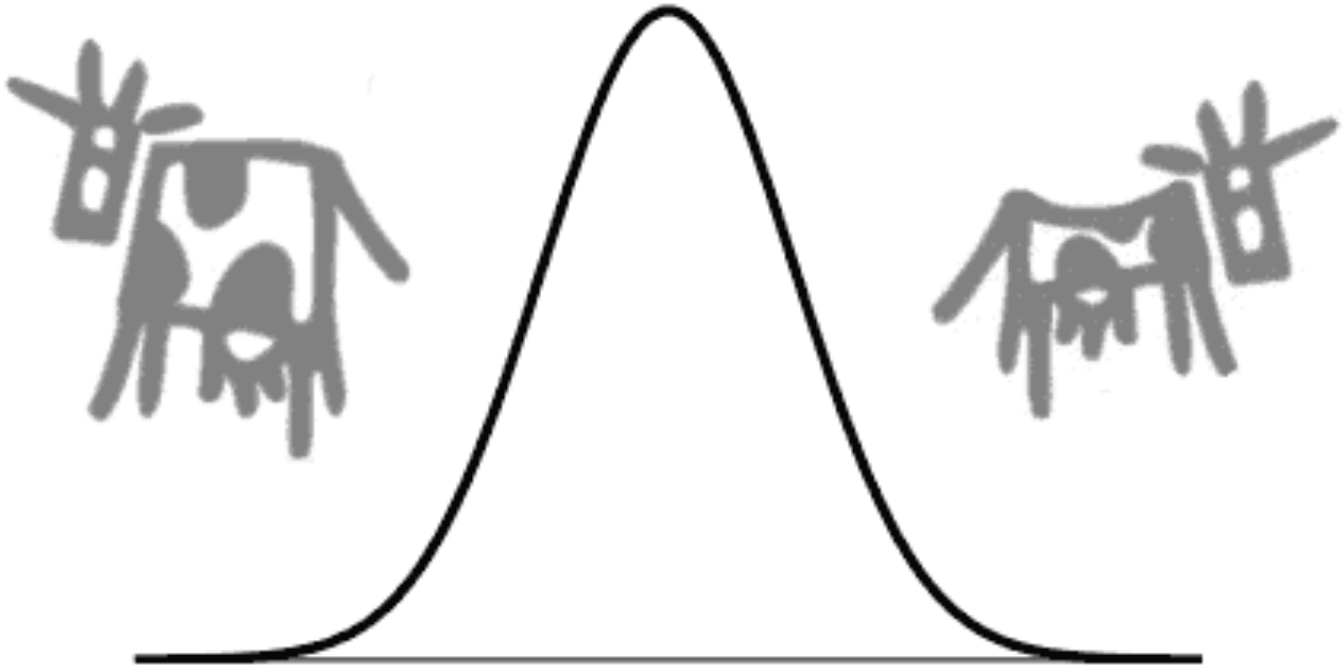
By Heather Timmons

Published: October 30, 2007

The New York Times

Oil prices reached a record high on Tuesday, rising more than 2 percent over the previous high of $91.86 on F

Fat Cows, Lean Cows



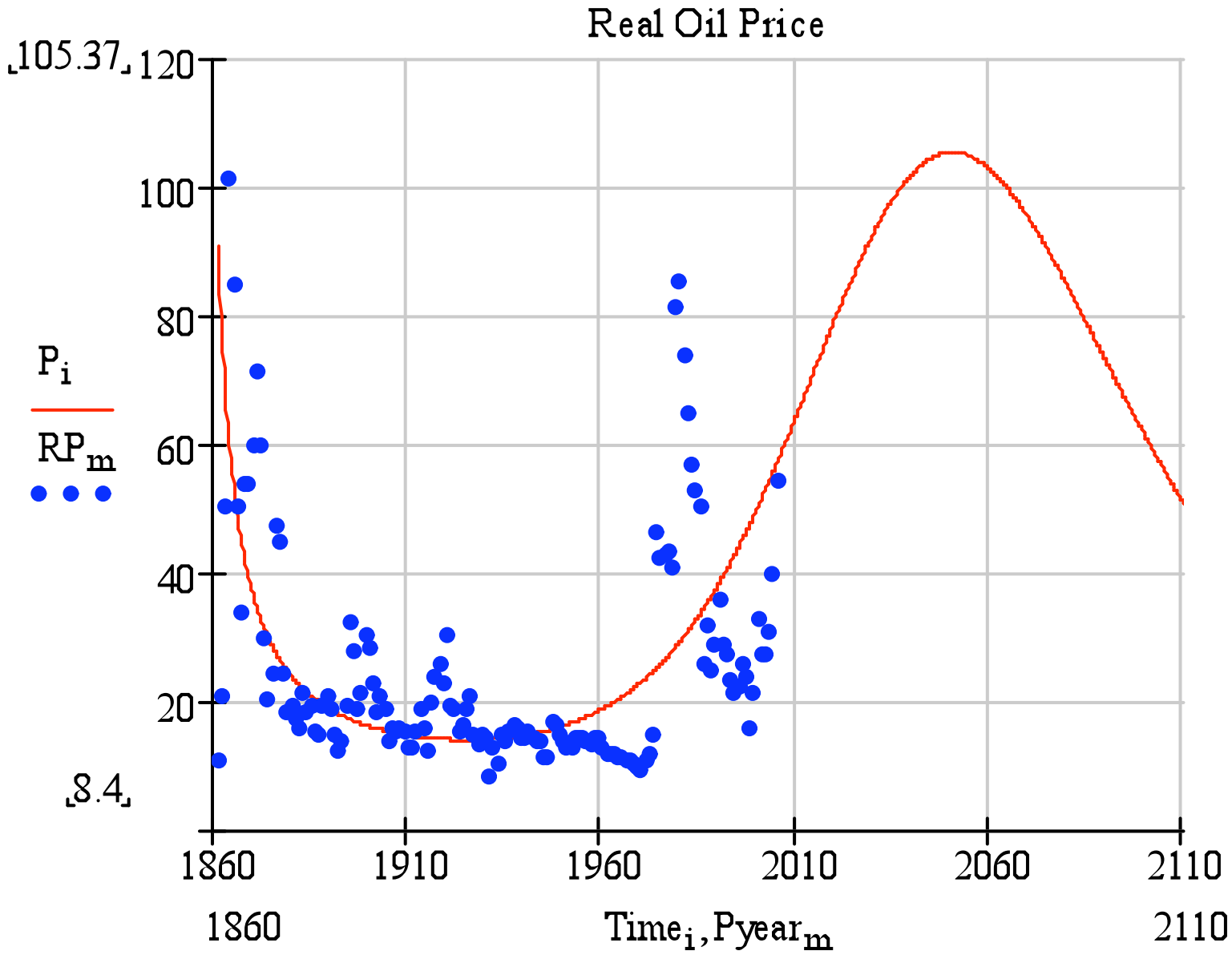
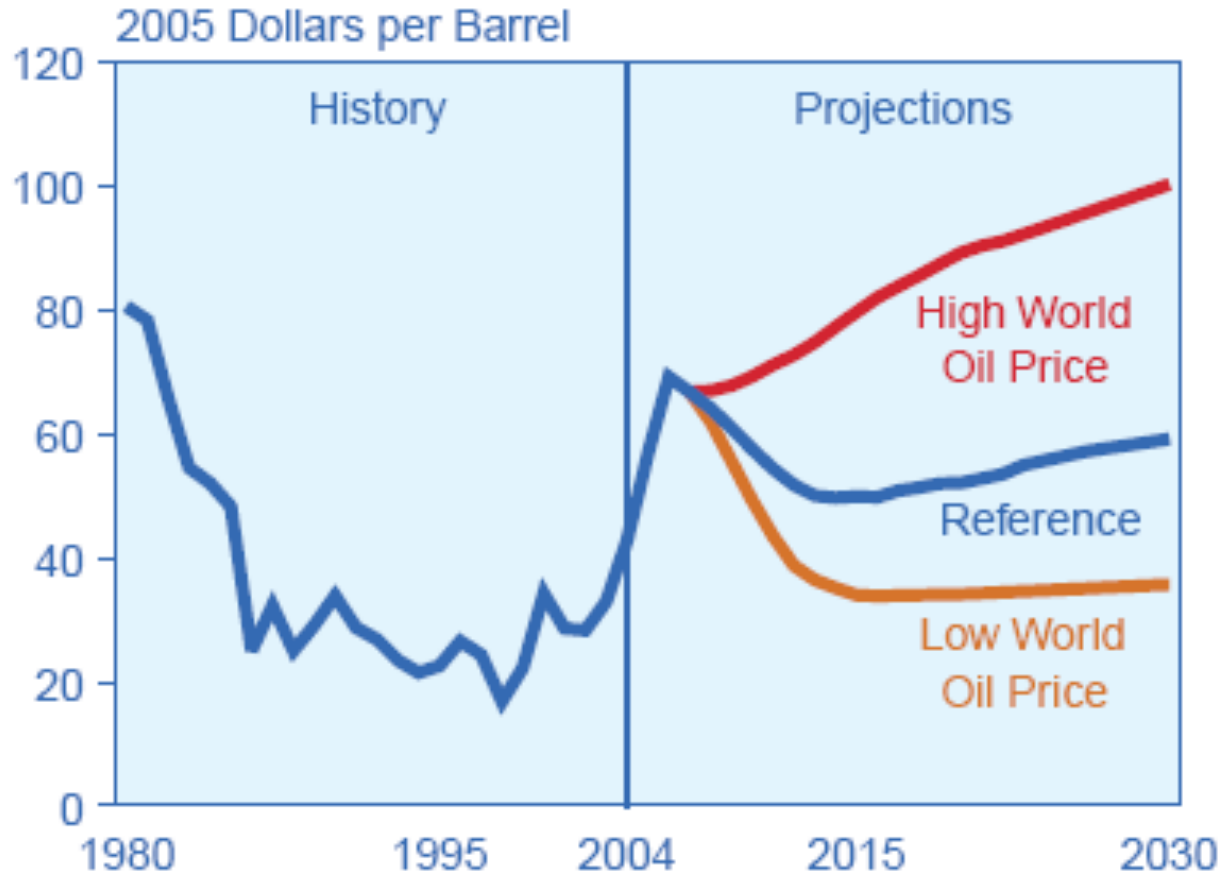
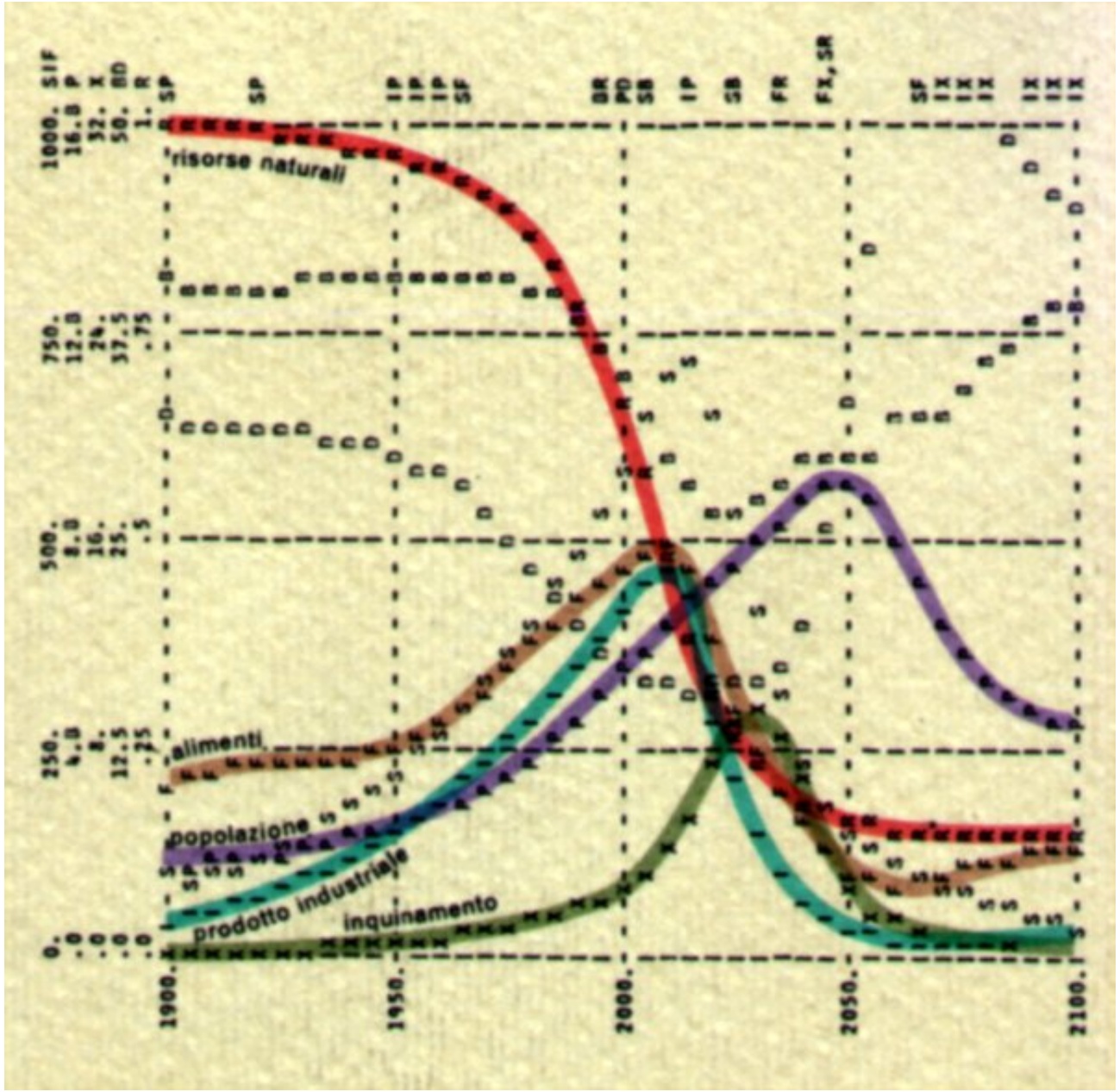

Real Oil Price
105.37
120
100
80
60
40
20
8.4
P_i
RP_m
1860
1910
1960
2010
2060
2110
1860
$Time_i, Pyear_m$
2110

Figure 17. World Oil Prices in Three World Oil Price Cases, 1980-2030

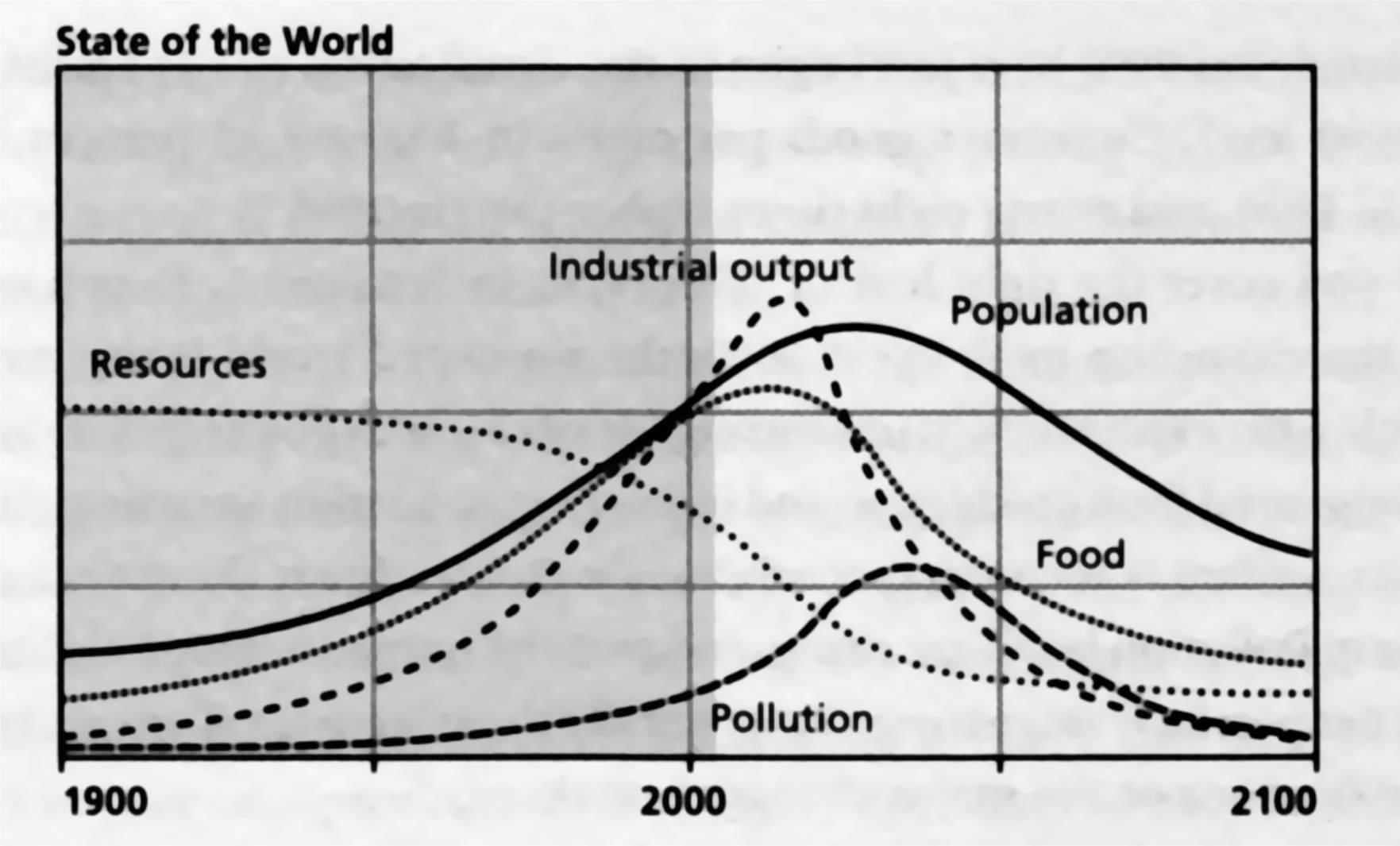


Source: Energy Information Administration (EIA), *Annual Energy Outlook 2007*, DOE/EIA-0383(2007) (Washington, DC, February 2007), web site www.eia.doe.gov/oiaf/aeo.

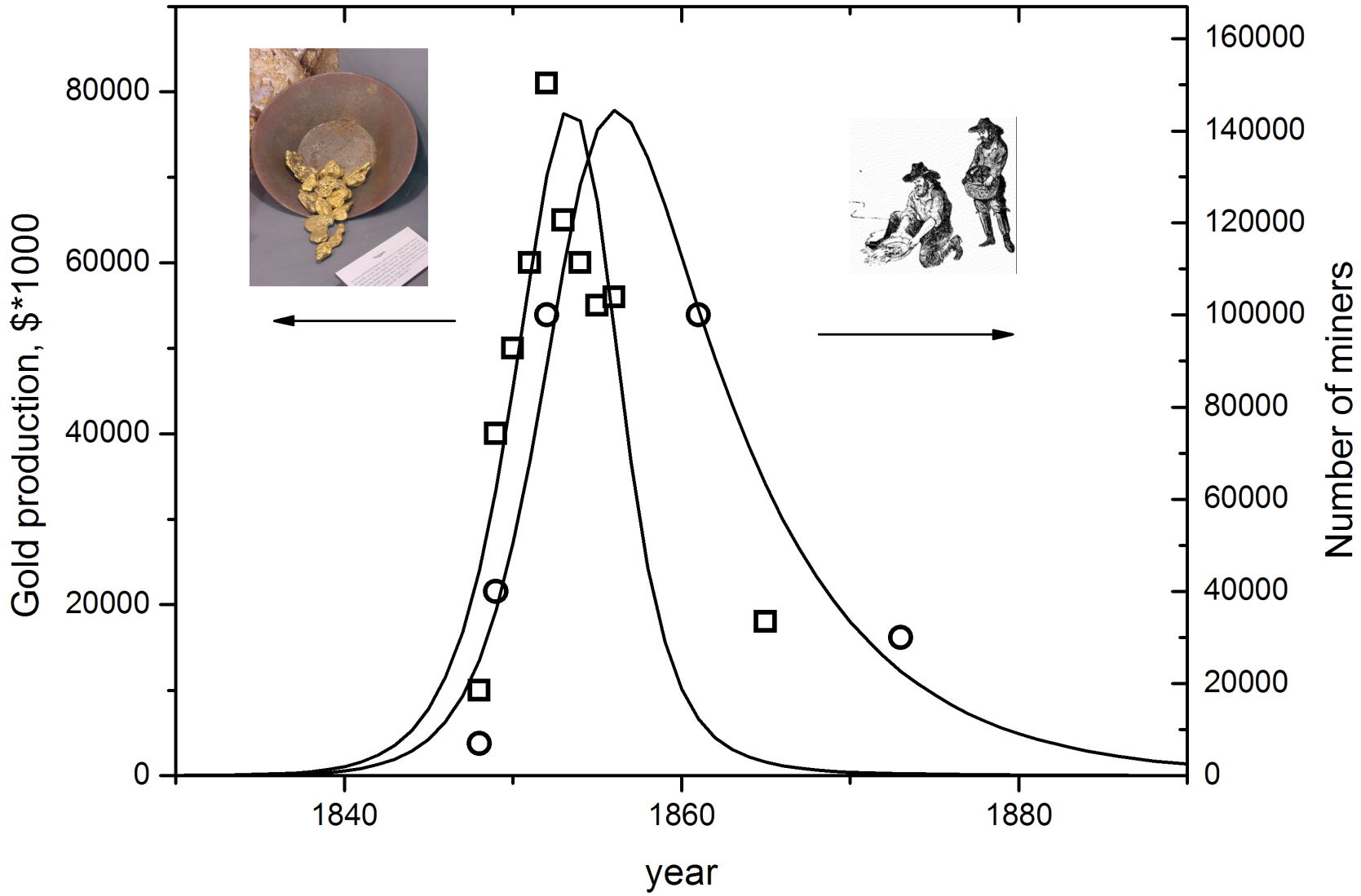
“Limits to Growth”, 1972



Limits to growth 2004

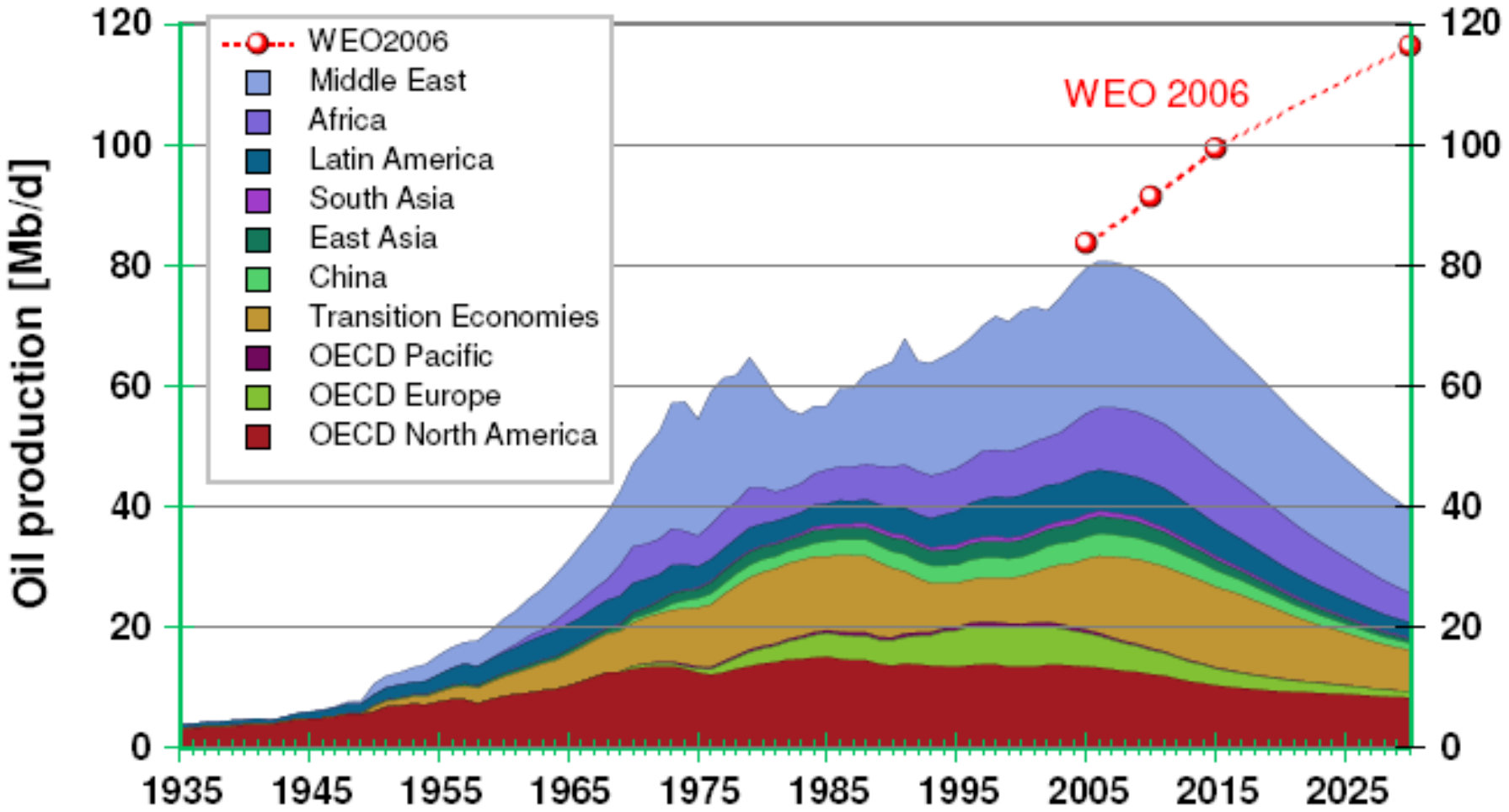


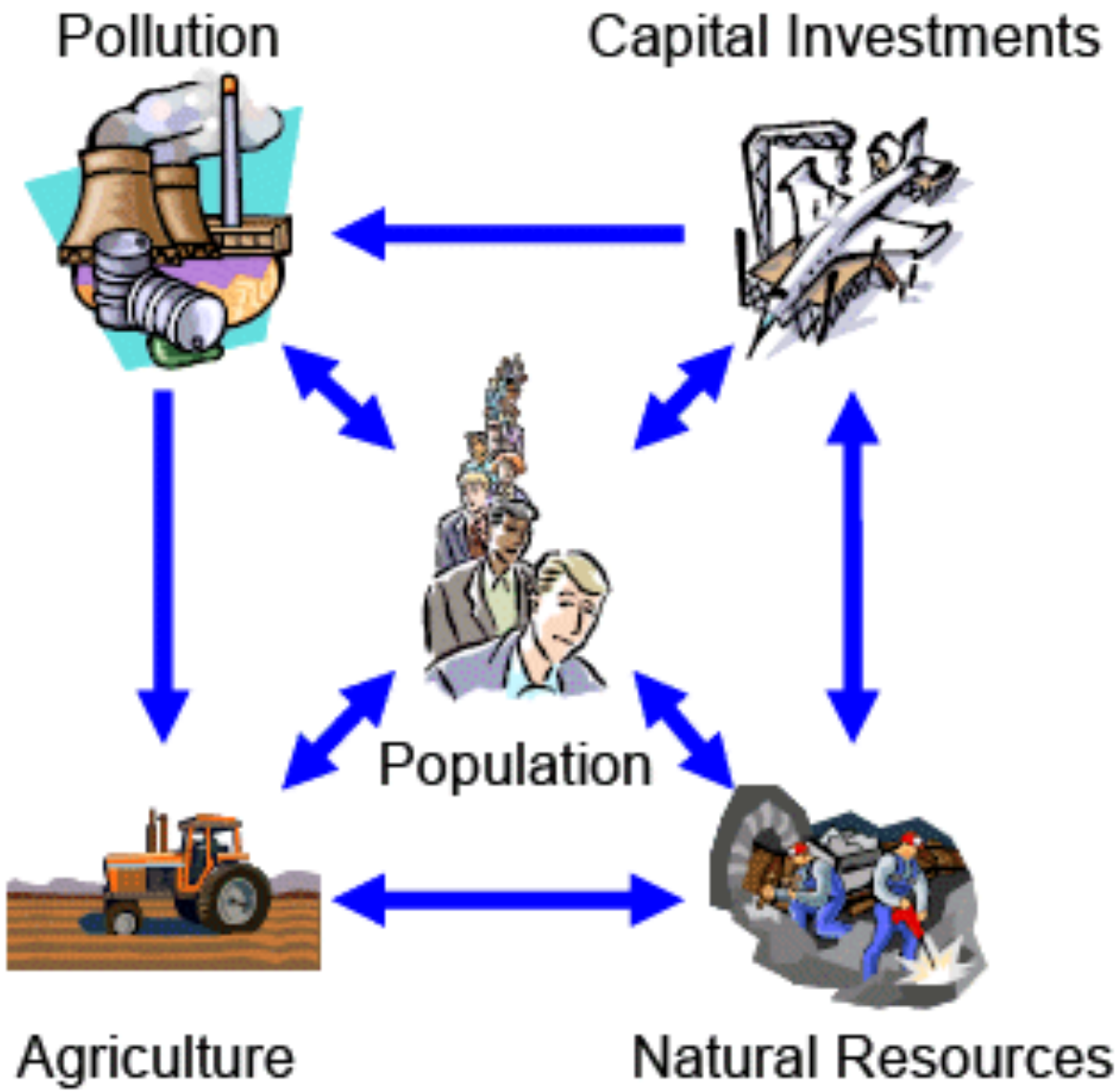
La Grande Corsa all'Oro della California

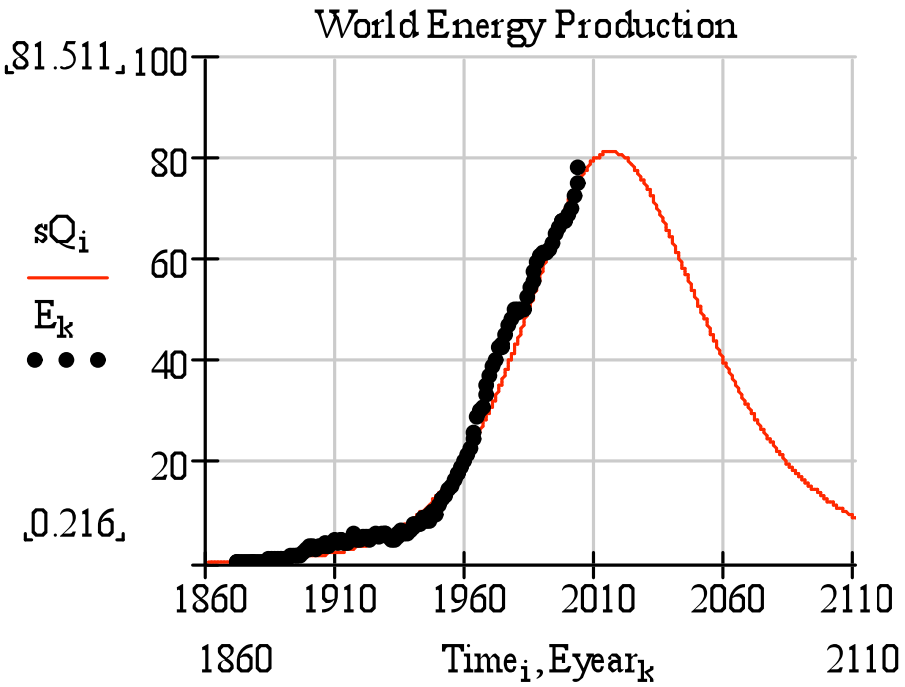


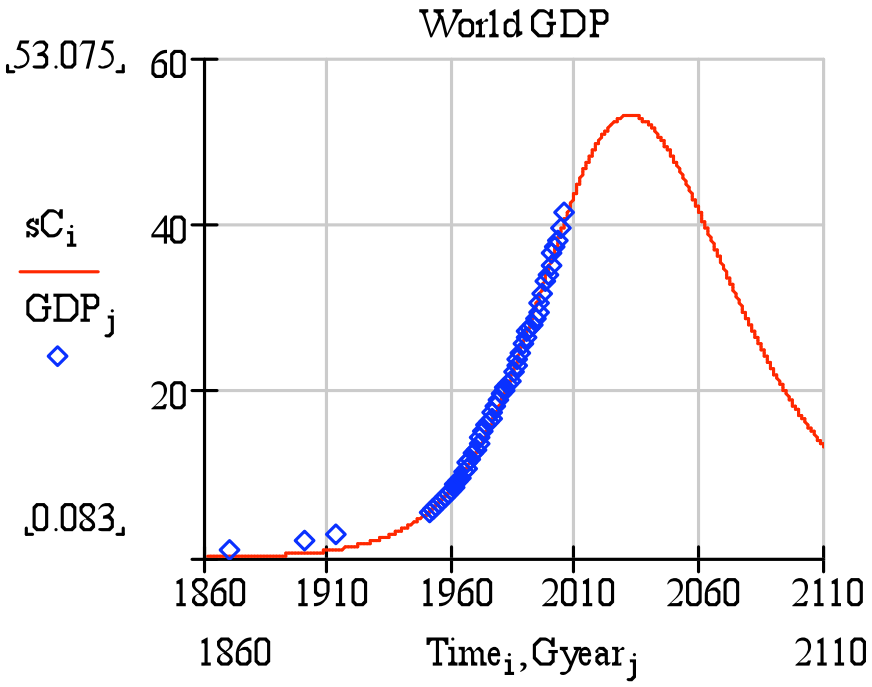
Energy Watch Group, 2007

Figure 7: Oil production world summary



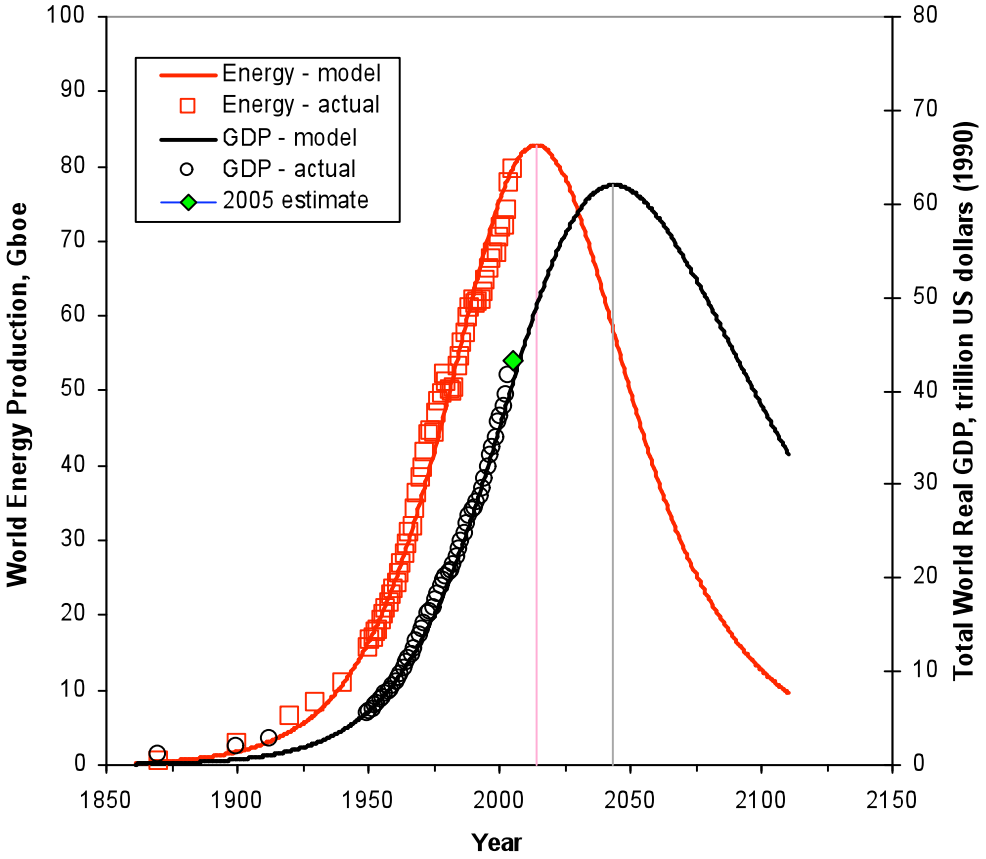

Pollution
Capital Investments
Population
Agriculture
Natural Resources


World Energy Production
81.511
100
80
60
40
20
0.216
sQ_i
E_k
1860
1910
1960
2010
2060
2110
1860
Time_i, Eyear_k
2110


World GDP
53.075
60
40
20
0.083
sC_i
GDP_j
1860
1910
1960
2010
2060
2110
1860
Time_i, Gyear_j
2110

This is an interesting exercise. We suppose that the “prey” in the model is fossil energy, where

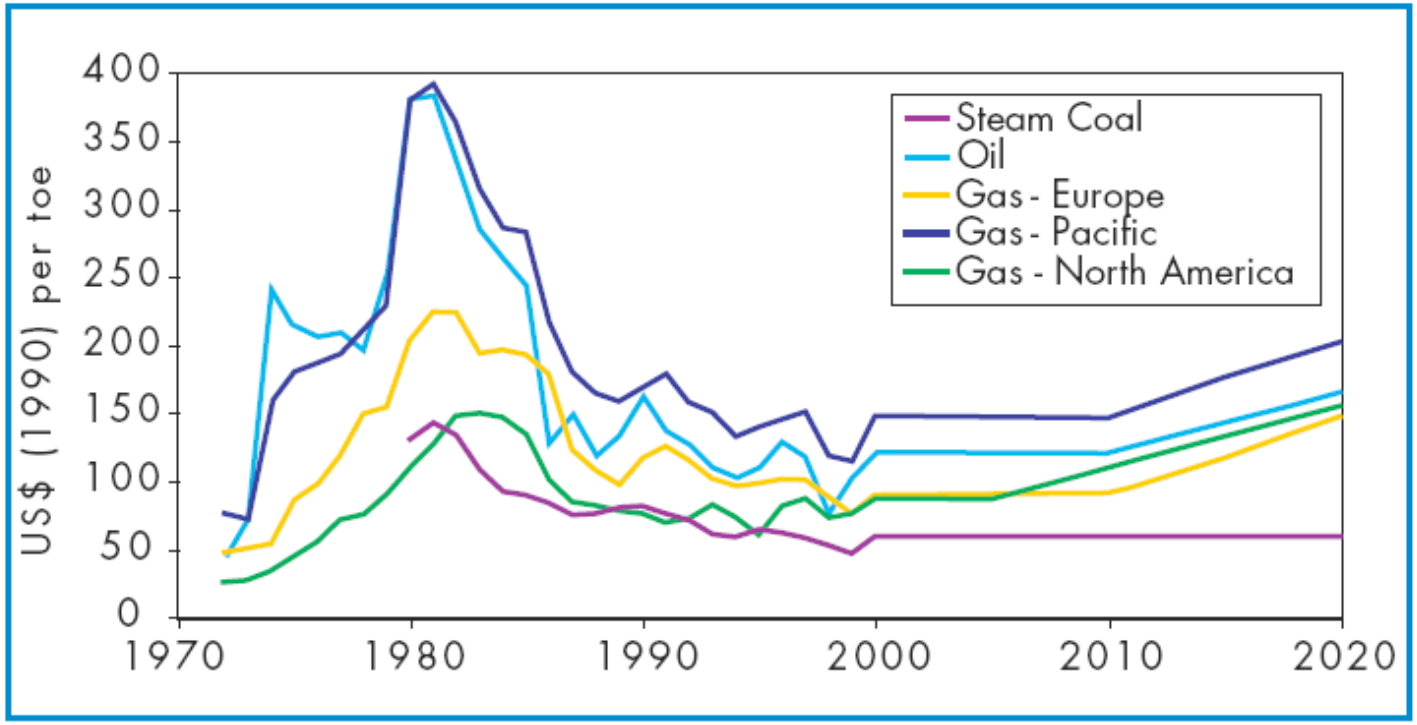
LV Model - Total World Energy



- Total World Energy Production Peak ± 2014
- Total World GDP Peak ± 2044

The Reference Scenario assumes an average IEA real crude-oil import price between 2000

Figure 1.4: **Assumptions for World Fossil Fuel Prices**



Note: Gas prices are expressed on a net calorific value basis.

2 pence coin minted until 1991
ca. 2.5 eurocent
7.12 g bronze
value ca. 3 Eurocent or 2.5 pence

10 eurocent coin
4.1 g Cu-Ni alloy
value ca 1.5 Eurocent

1 Euro = 80 pence