Lecture – 7A

Energy Resources, Economics and Environment

Energy Resources

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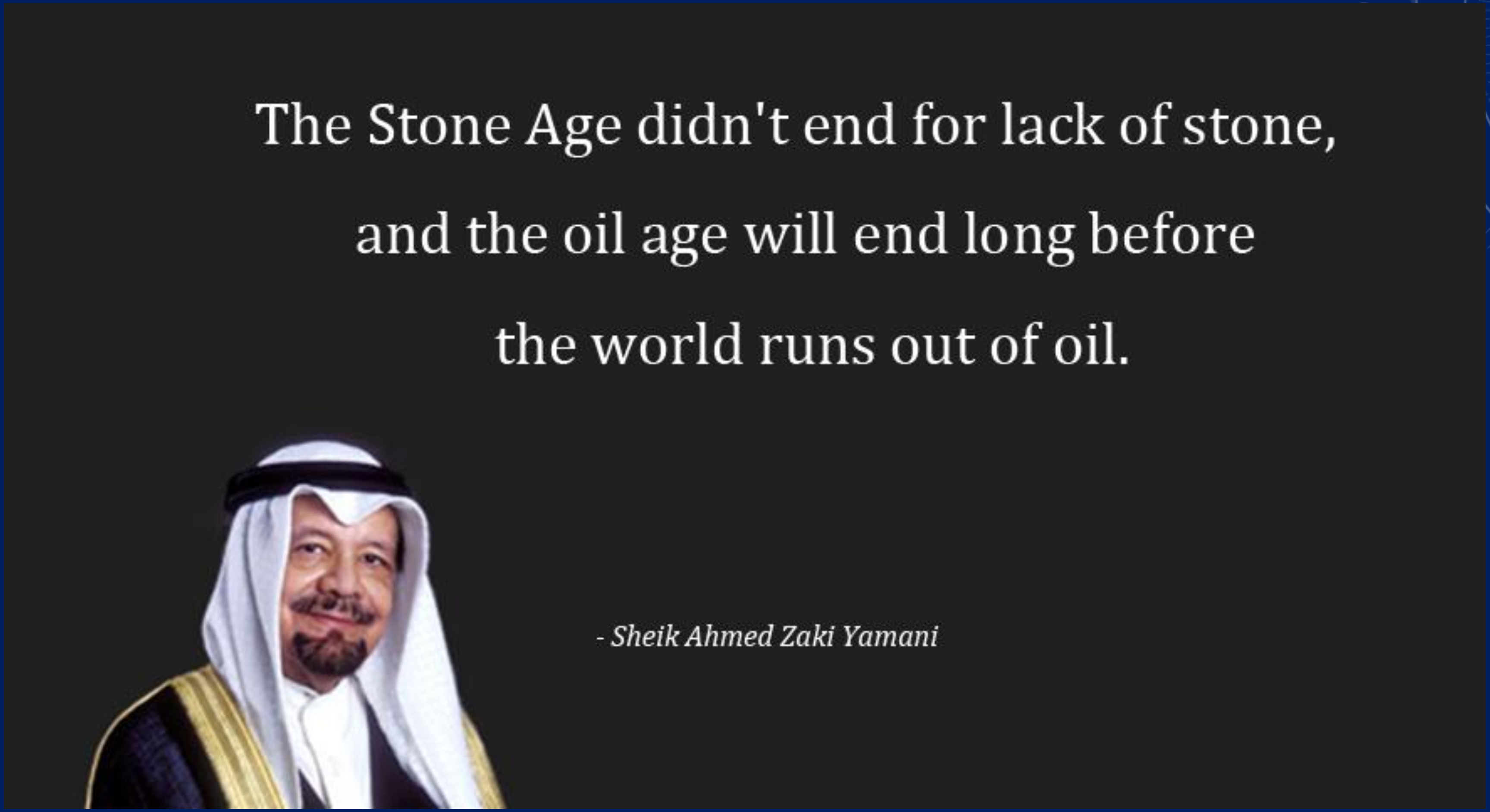
Some questions

- What is peak oil?
- Do you believe in peak oil, peak coal? Peak natural gas?
- Are fossil fuels depletable?
- Will their consumption decline?
- How long will they last?

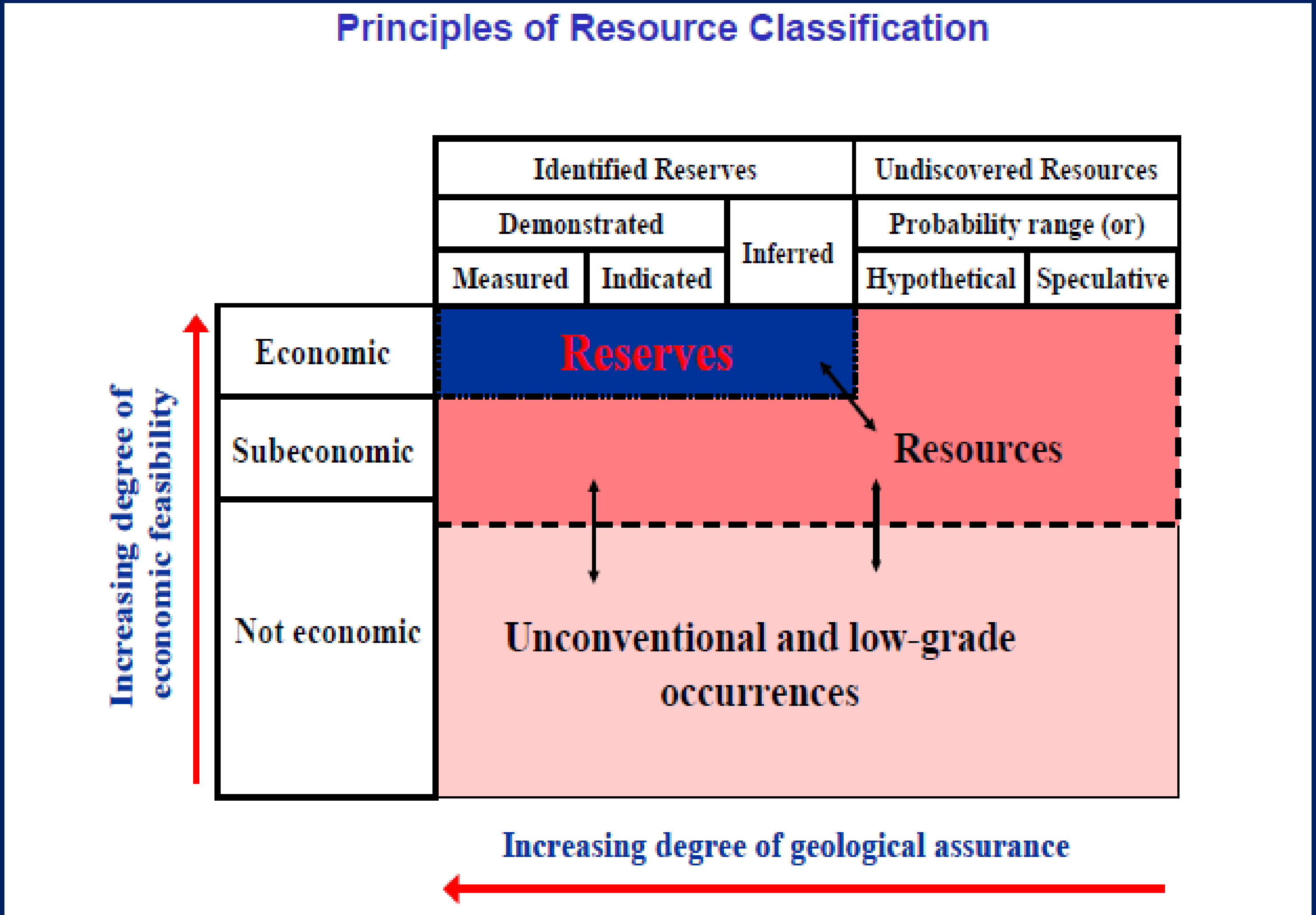
End of Oil age?



Saudi Arabian Oil Minister

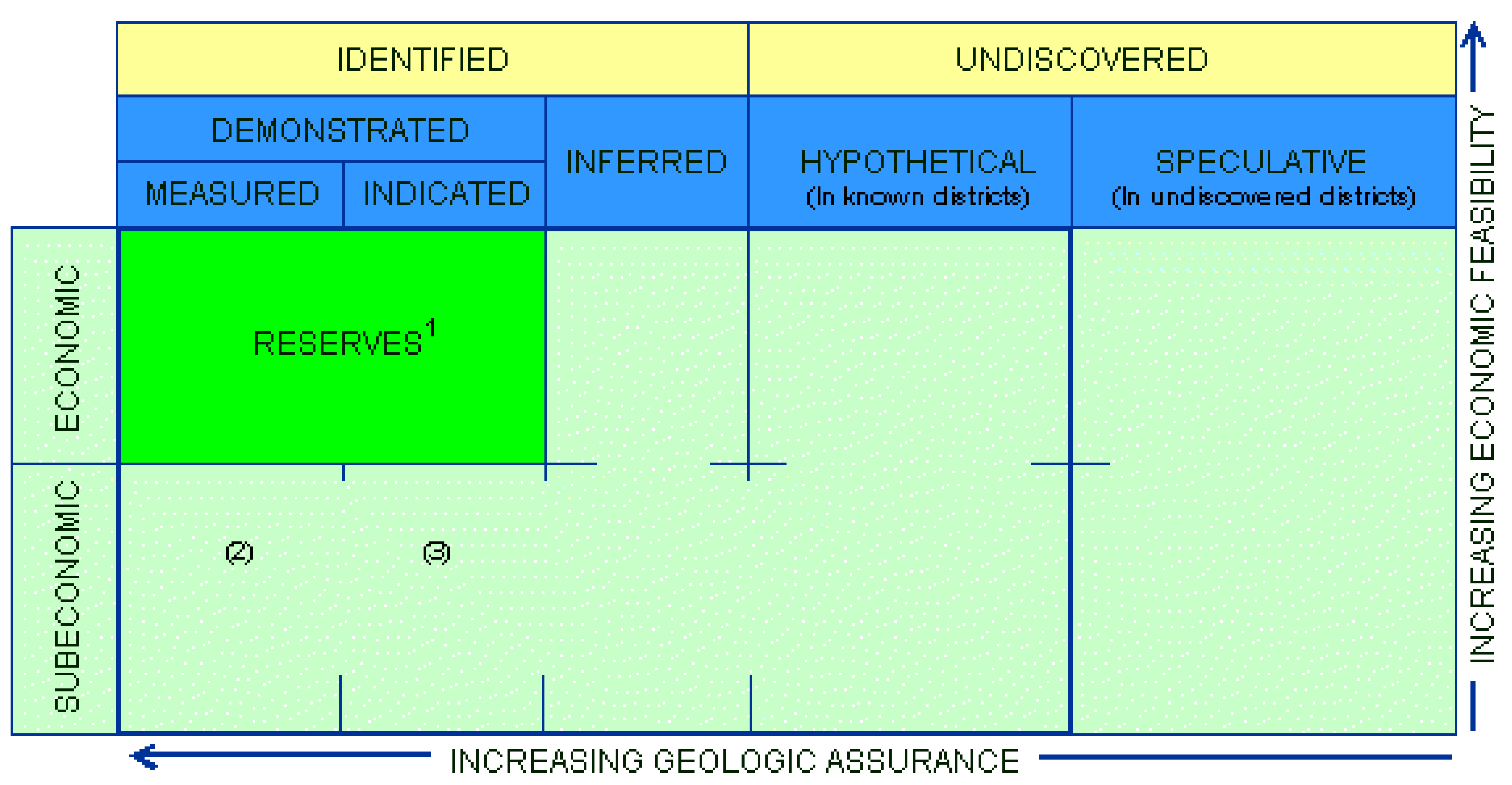
http://www.energypost.eu/wp-content/uploads/2015/01/yamani-quote.png

McKelvey Diagram



Source: GEA Chapter 7

McKelvey Diagram



https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/thumbnails/image/1450_F1.gif

Issues / Questions

- Energy Resources- Cornucopia or Empty Barrel? (Mc Cabe, 1998)
- Estimates of time period till shortage
- Classification – Renewable/ Depletable (Exhaustible)

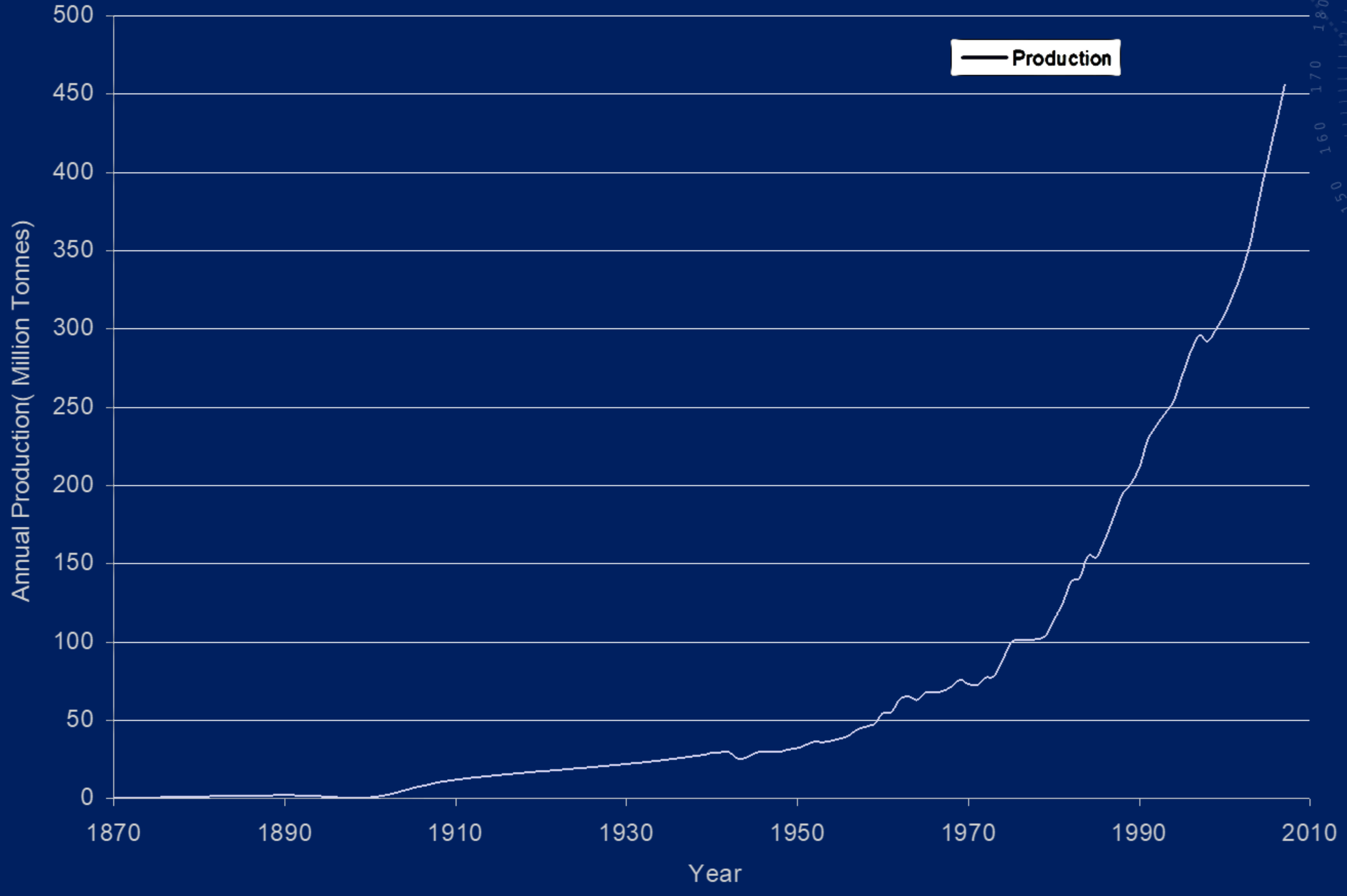
Estimates of time

- Static R/P ratio
- Exponential growth
- Logistic growth curve – area under curve bounded – finite resource
- Adelmans model

Resource and Reserve

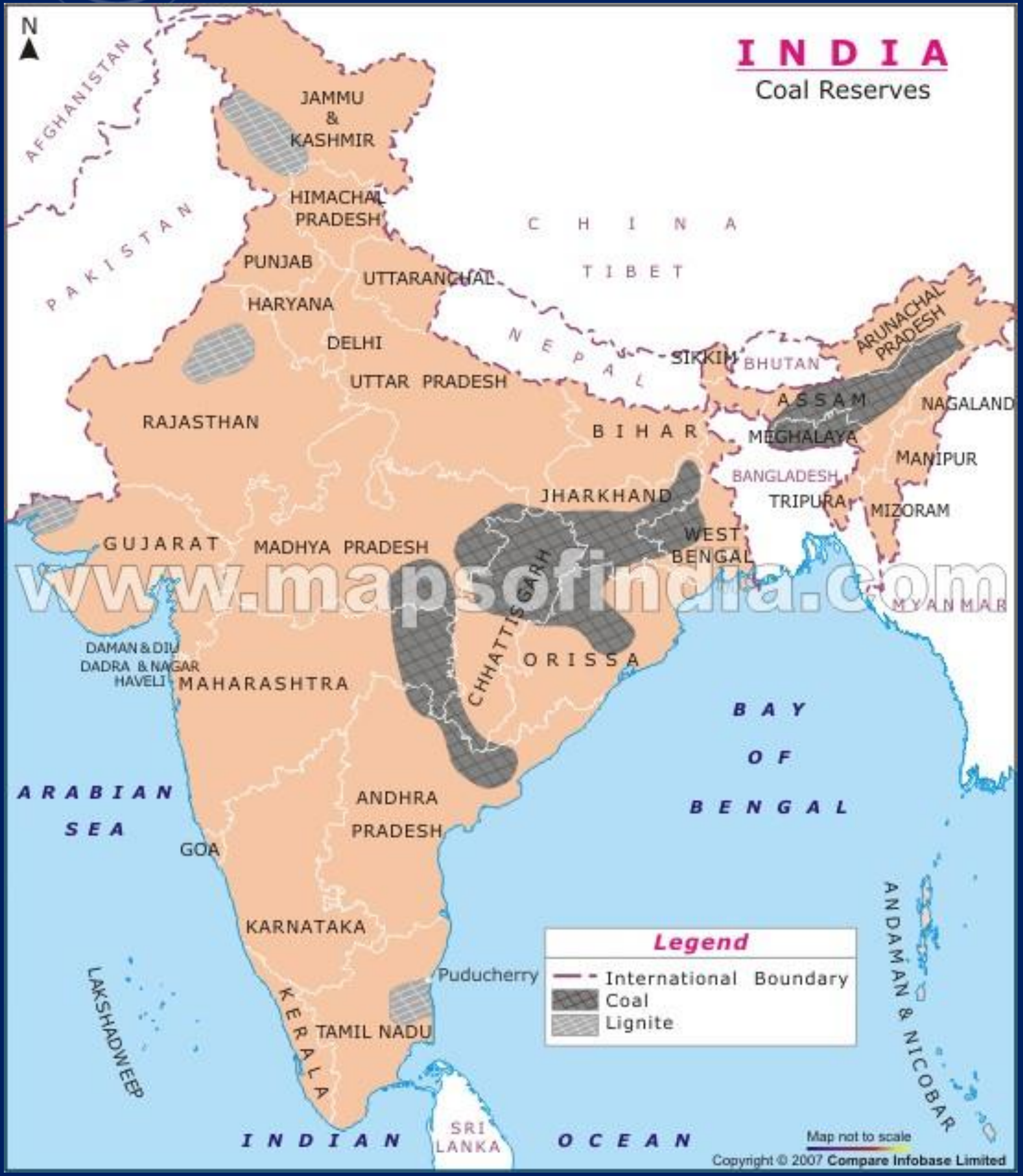
- Reserve - Identified Accumulations that can be extracted profitably under present economic conditions
- Resource – reserves plus all accumulations that may eventually may become available (yet undiscovered, or discovered but currently not technically or economically viable)

Coal Production in India



India

Coal Reserves



Source: www.mapsofindia.com

India - Fossil Fuel reserves

Fuel	Reserves	Prodn 2003-4	R/P ratio
Coal +Lignite (Million Tonnes)	34000	414	~83 (P) 140 P+I
Oil (Million Tonnes)	760	33 (117)	23 (7)
N.Gas Billion m3	920	32	29
Uranium Tonnes	61000	PHWR	~50 10GW

Data Source Plg Comm IEPC, 2006

India - Fossil Fuel reserves

Fuel	Reserves	Prodn 2013-14	R/P ratio
Coal +Lignite(Million Tonnes)	132090	571	
Oil (Million Tonnes)	763	38	
N.Gas Billion m3	1427	41/35	
Uranium Tonnes	61000	PHWR	~50 10GW

Data Source Ministry web sites GSI

India Coal Reserves

As on	Geological Resources of Coal			
	Proved	Indicated	Inferred	Total
1.4.2009	105820	123470	37920	267210
1.4.2010	109798	130654	36358	276810
1.4.2011	114002	137471	34390	285862
1.4.2012	118145	142169	33183	293497
1.4.2013	123182	142632	33101	298914

As on	Geological Resources of Coal			
	Proved	Indicated	Inferred	Total
1.4.2014	125909	142506	33149	301564

Finite Resource constraint?

‘The total mineral in the earth is an irrelevant nonbinding constraint. If expected finding-development costs exceed the expected net revenues, investment dries up and the industry disappears. Whatever is left in the

ground is unknown, probably unknowable, but surely unimportant: a geological fact of no economic interest ‘

Adelman , 1990

References

- GEA, 2012: Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. Chapter 7
- http://www.energypost.eu/wp-content/uploads/2015/01/yamani-quote.png
- https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/thumbnails/image/1450_F1.gif
- Maps of India: https://www.mapsofindia.com/
- Planning Commission, IEPC, 2006
- Global Survey of India: (https://www.gsi.gov.in)

Lecture -7B

Energy Resources, Economics and Environment

Energy Resources

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Finite Resource constraint?

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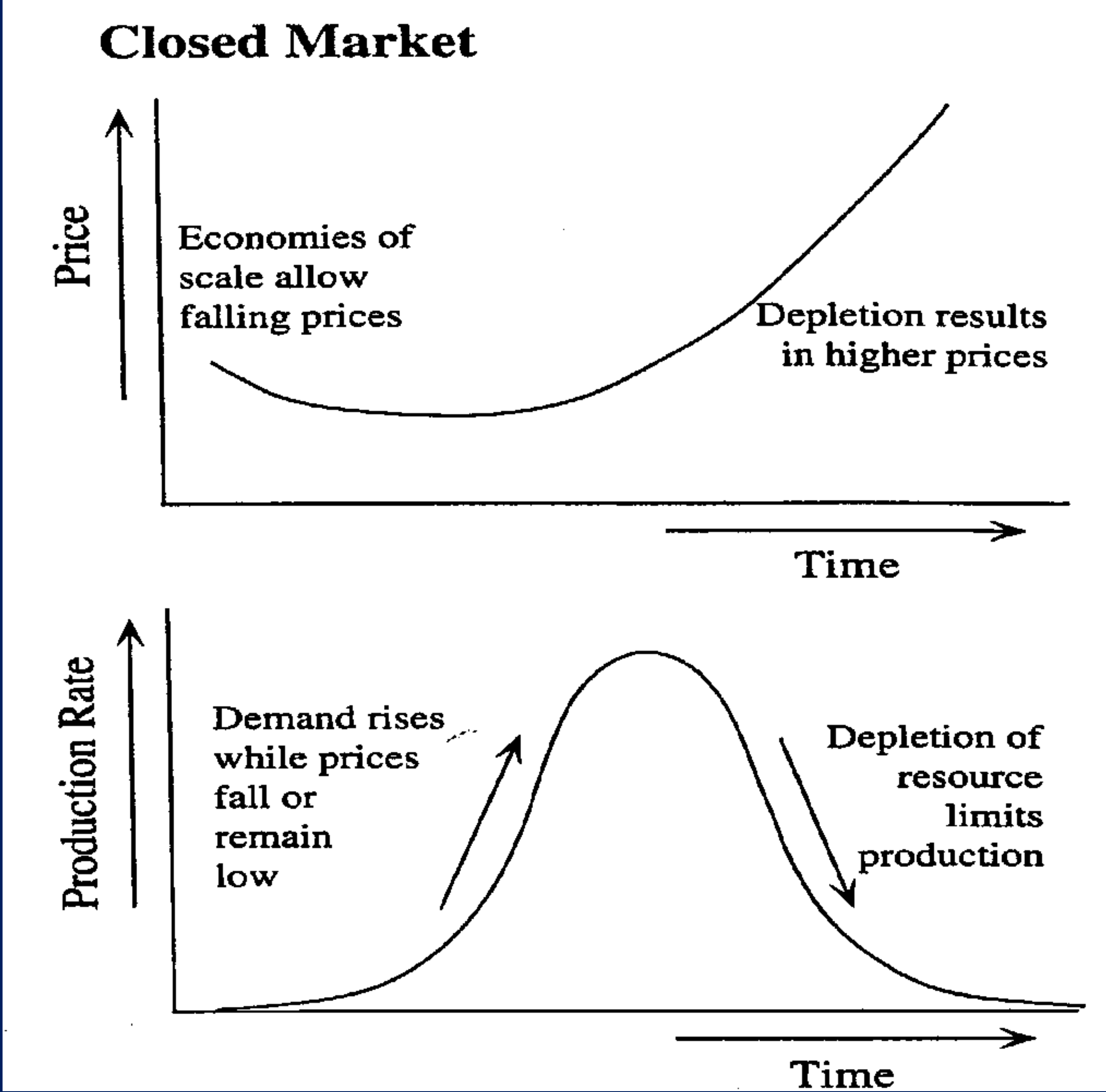
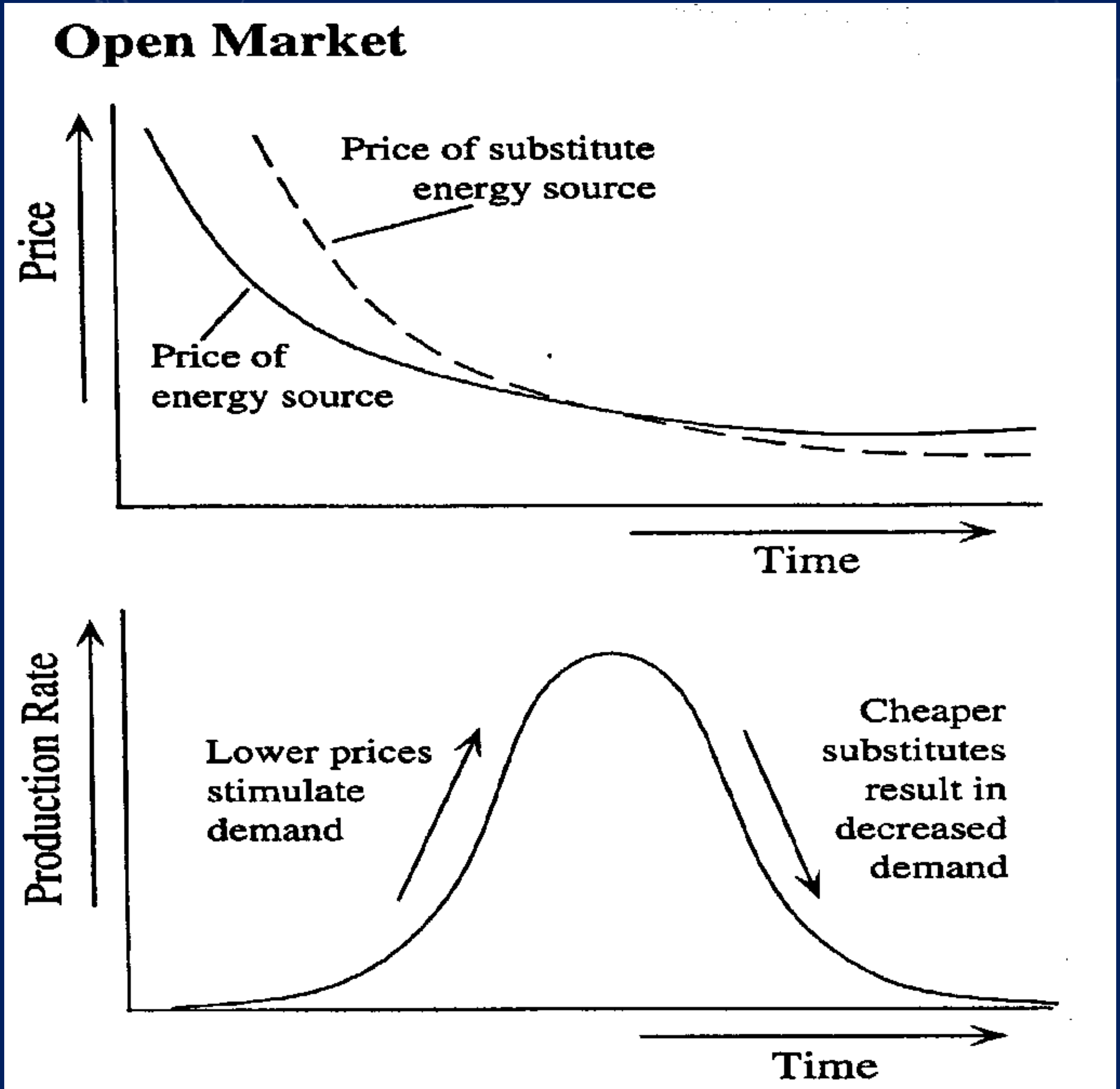
Adelman , 1990


Closed Market
Price
Economies of
scale allow
falling prices
Depletion results
in higher prices
Time
Production Rate
Demand rises
while prices
fall or
remain
low
Depletion of
resource
limits
production
Time

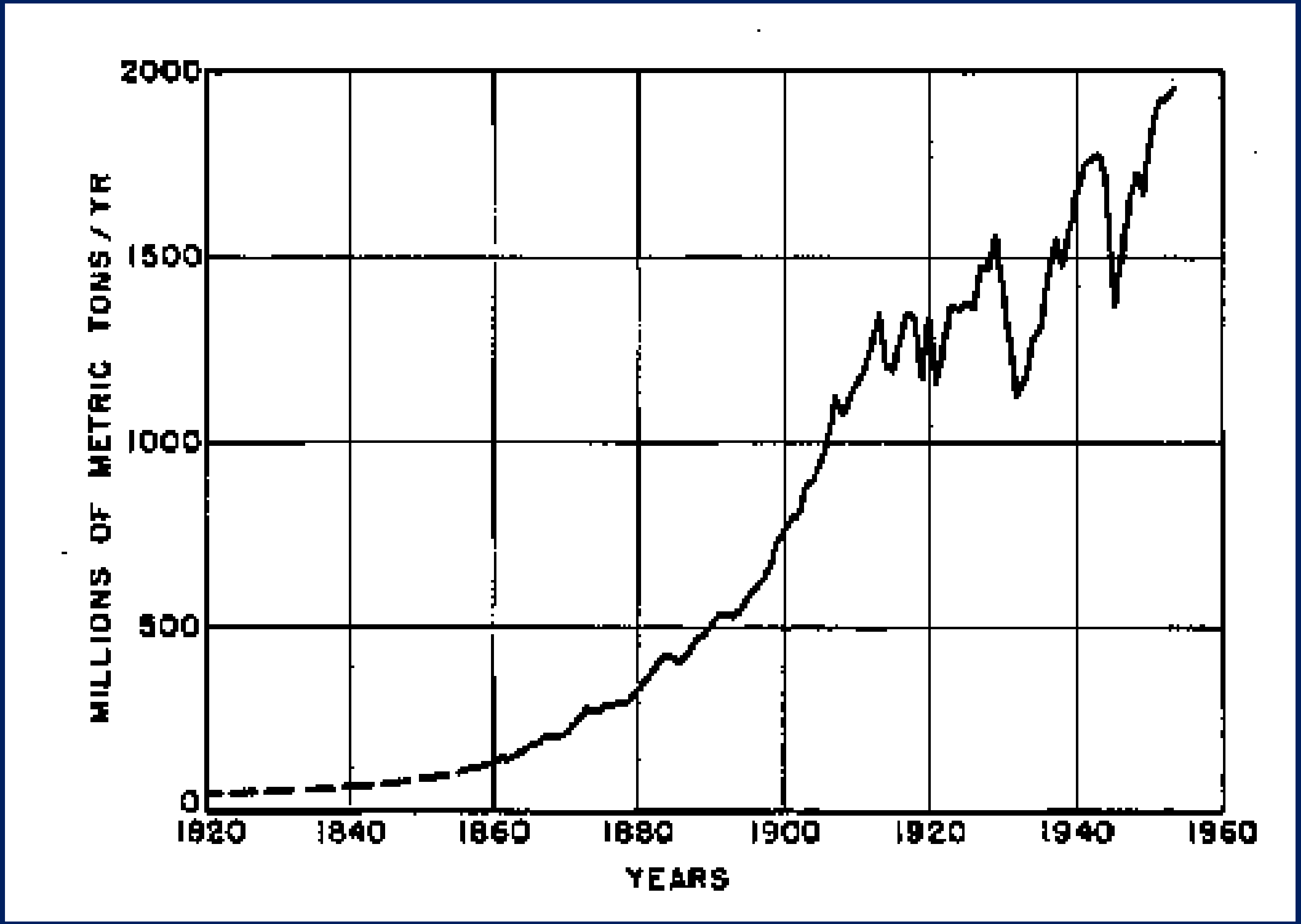
McCabe 1998



Open Market
Price
Price of substitute energy source
Price of energy source
Time
Production Rate
Lower prices stimulate demand
Cheaper substitutes result in decreased demand
Time

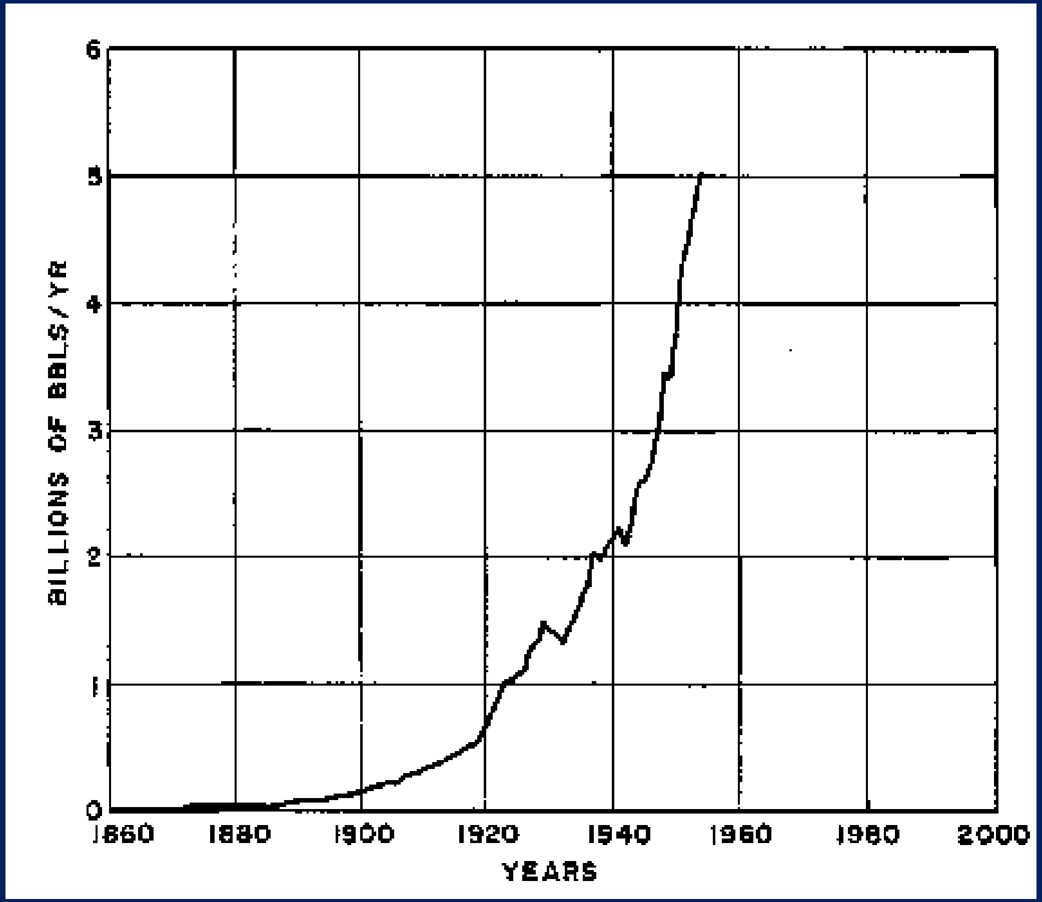
McCabe 1998

World production of Coal



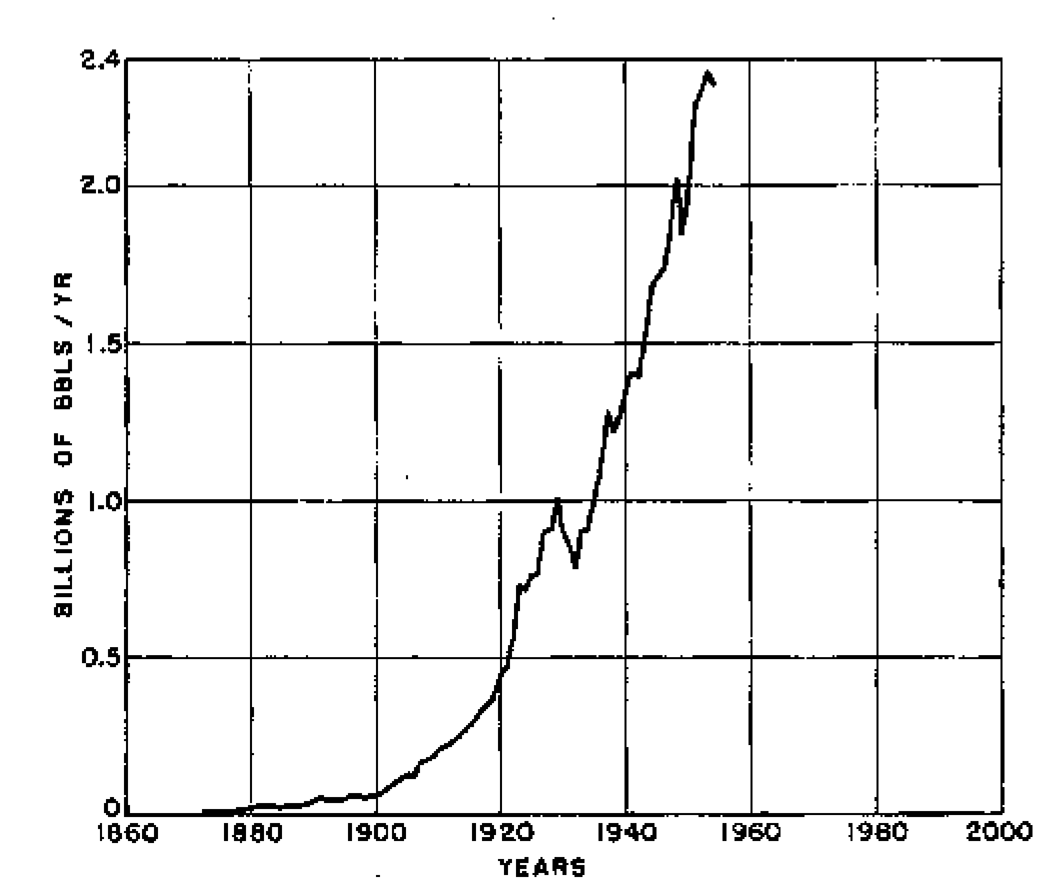
Source: M.K.Hubbert (1956) Shell

World production of Oil



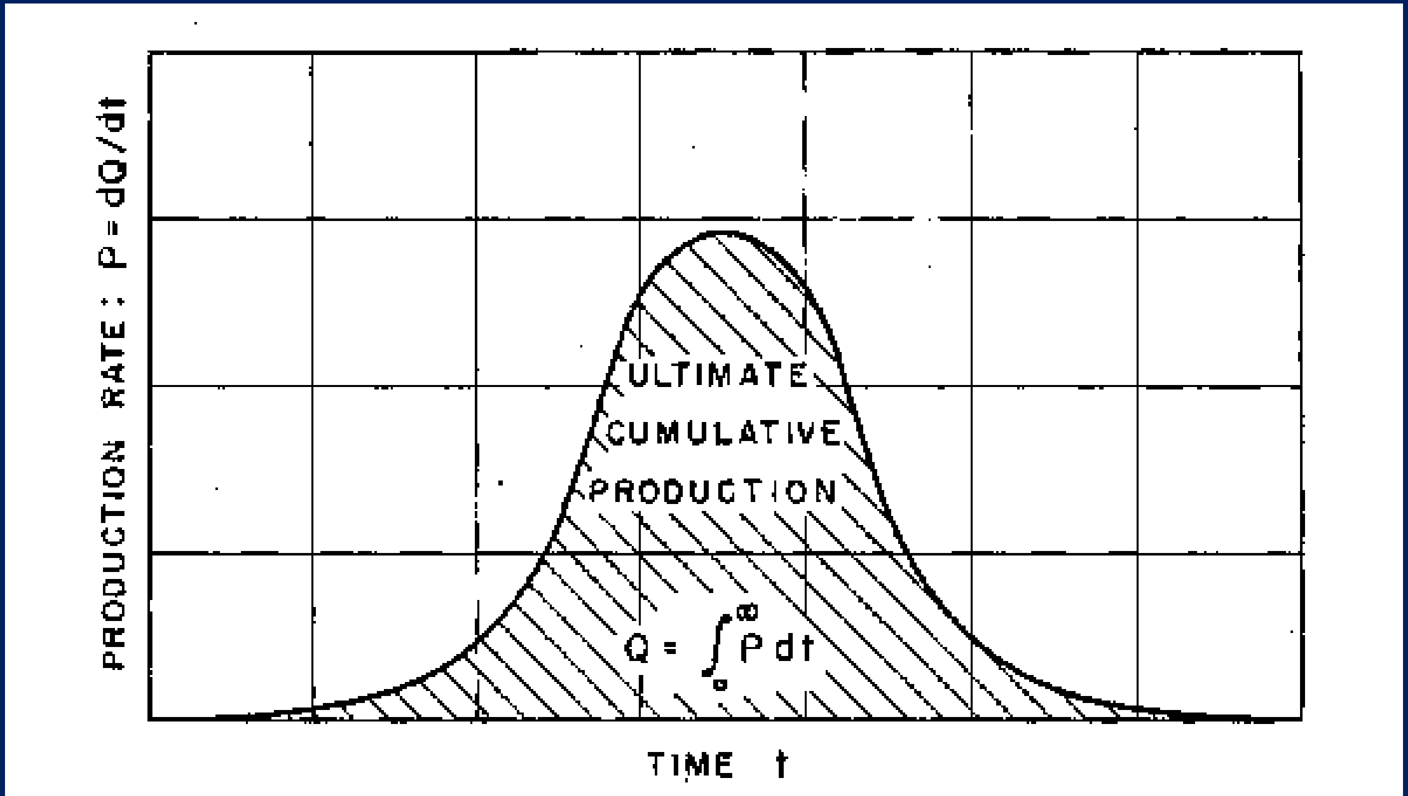
Source: M.K.Hubbert (1956) Shell

US production of crude Oil



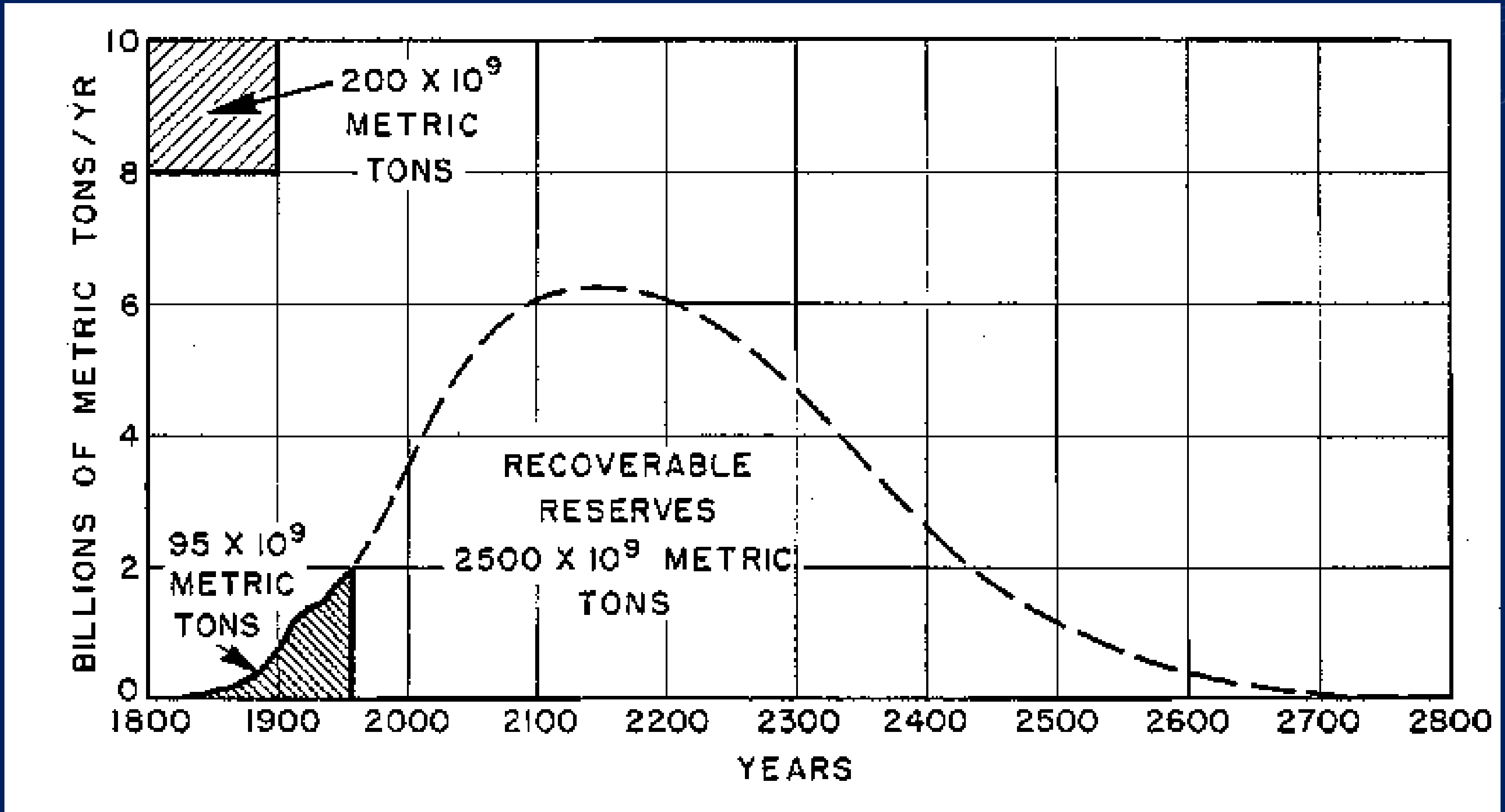
Source: M.K.Hubbert (1956) Shell

Production trend for exhaustible resource



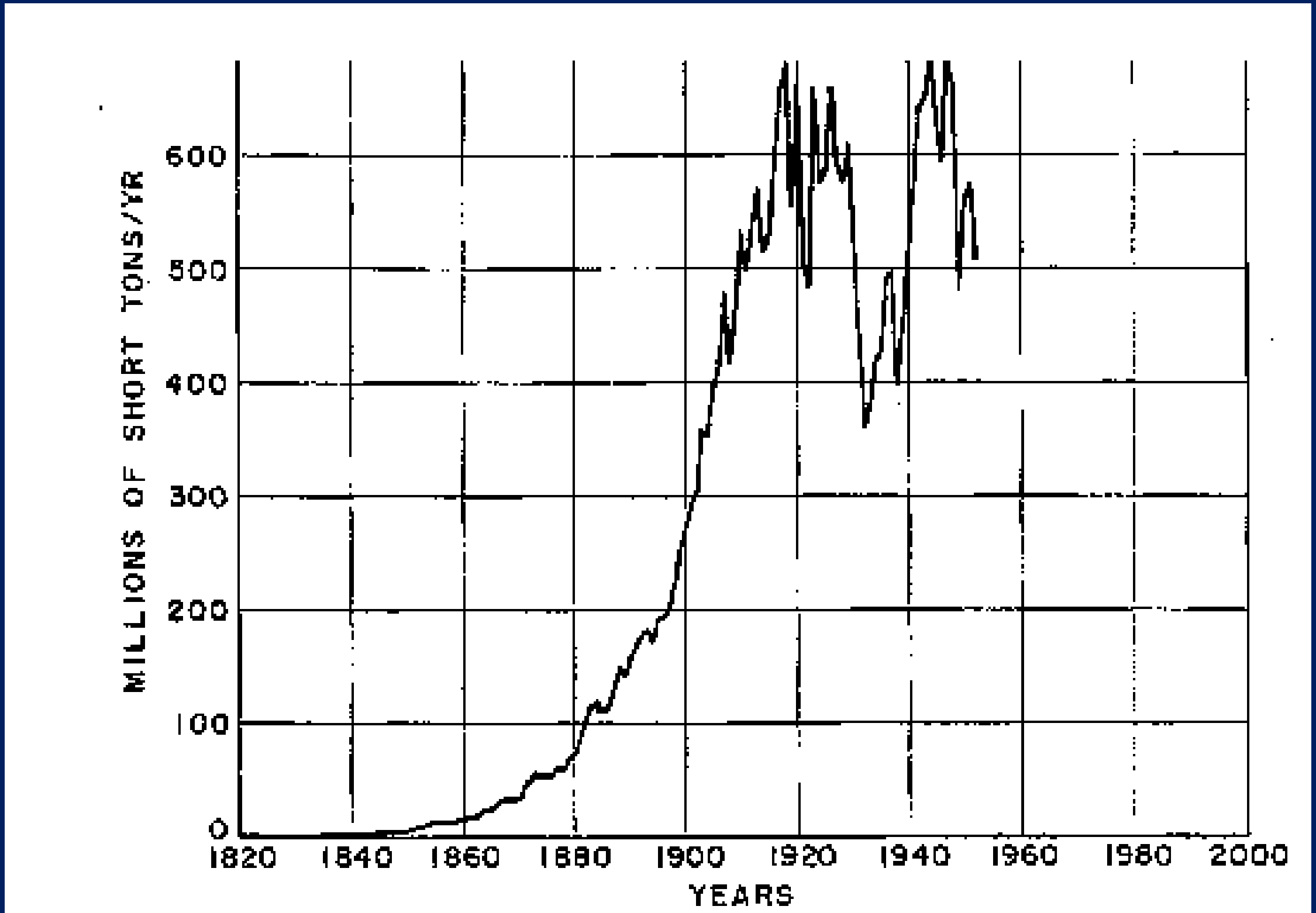
Source: M.K.Hubbert (1956) Shell

Ultimate World Coal Production



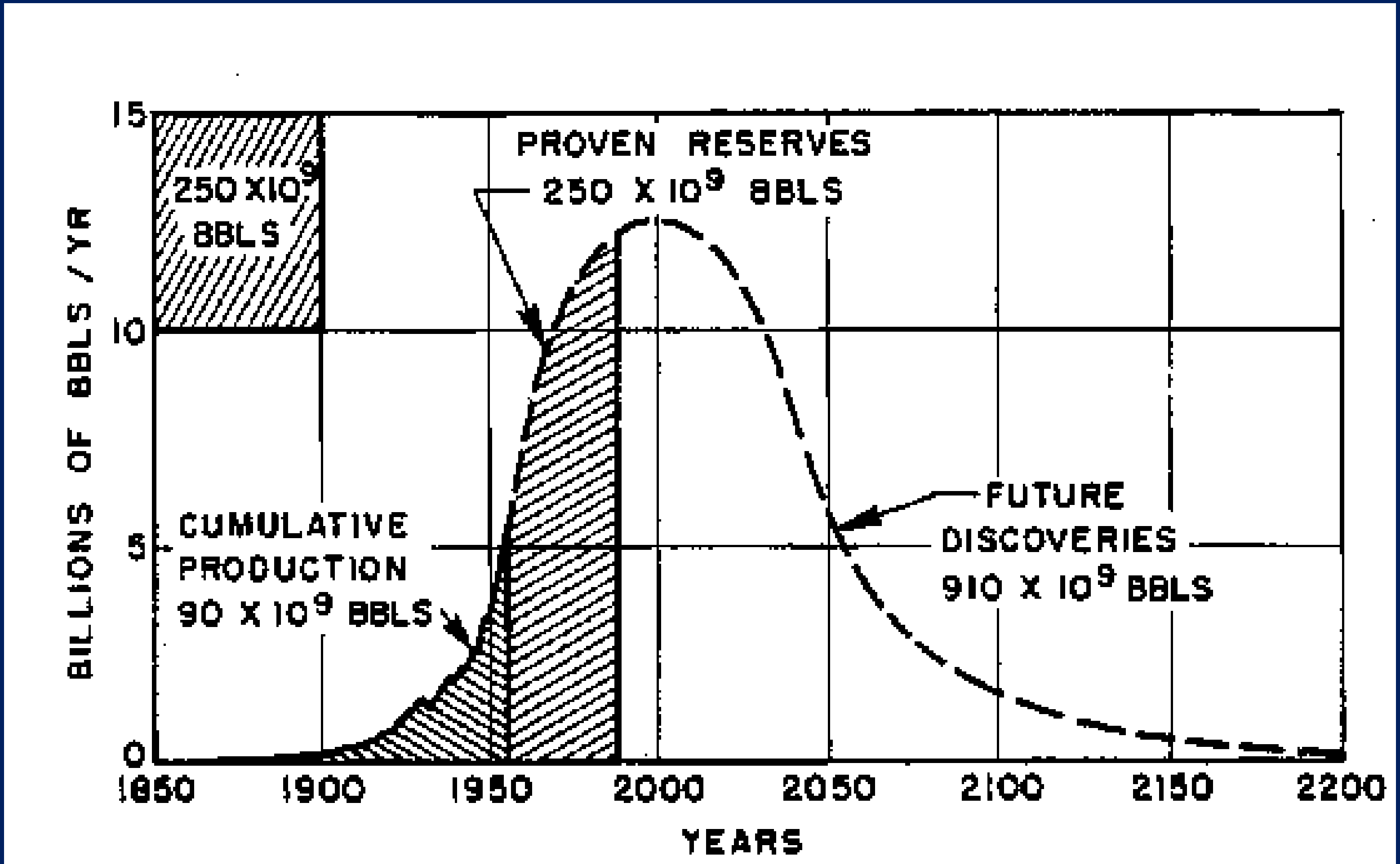
Source: M.K.Hubbert (1956) Shell

US production of coal



Source: M.K.Hubbert (1956) Shell

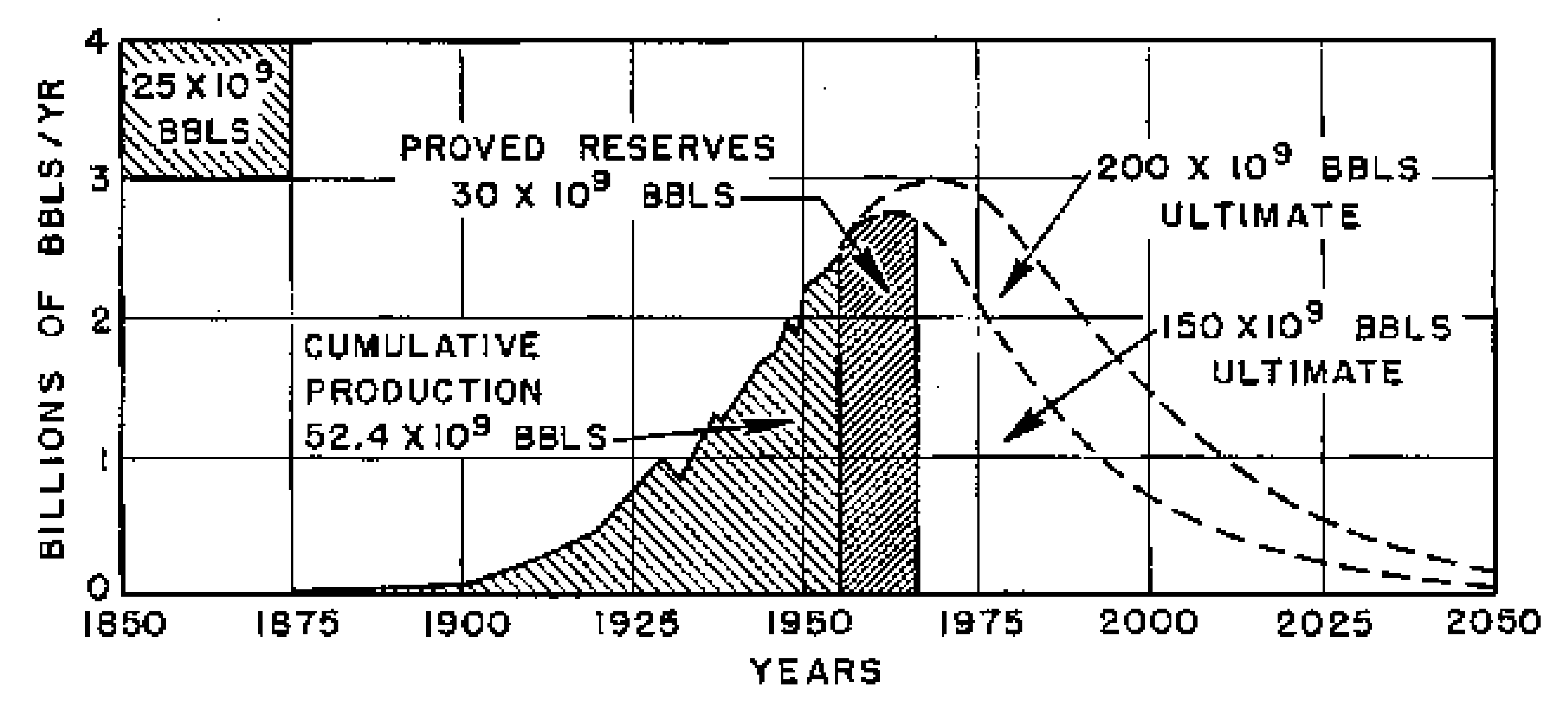
Ultimate World Oil Production



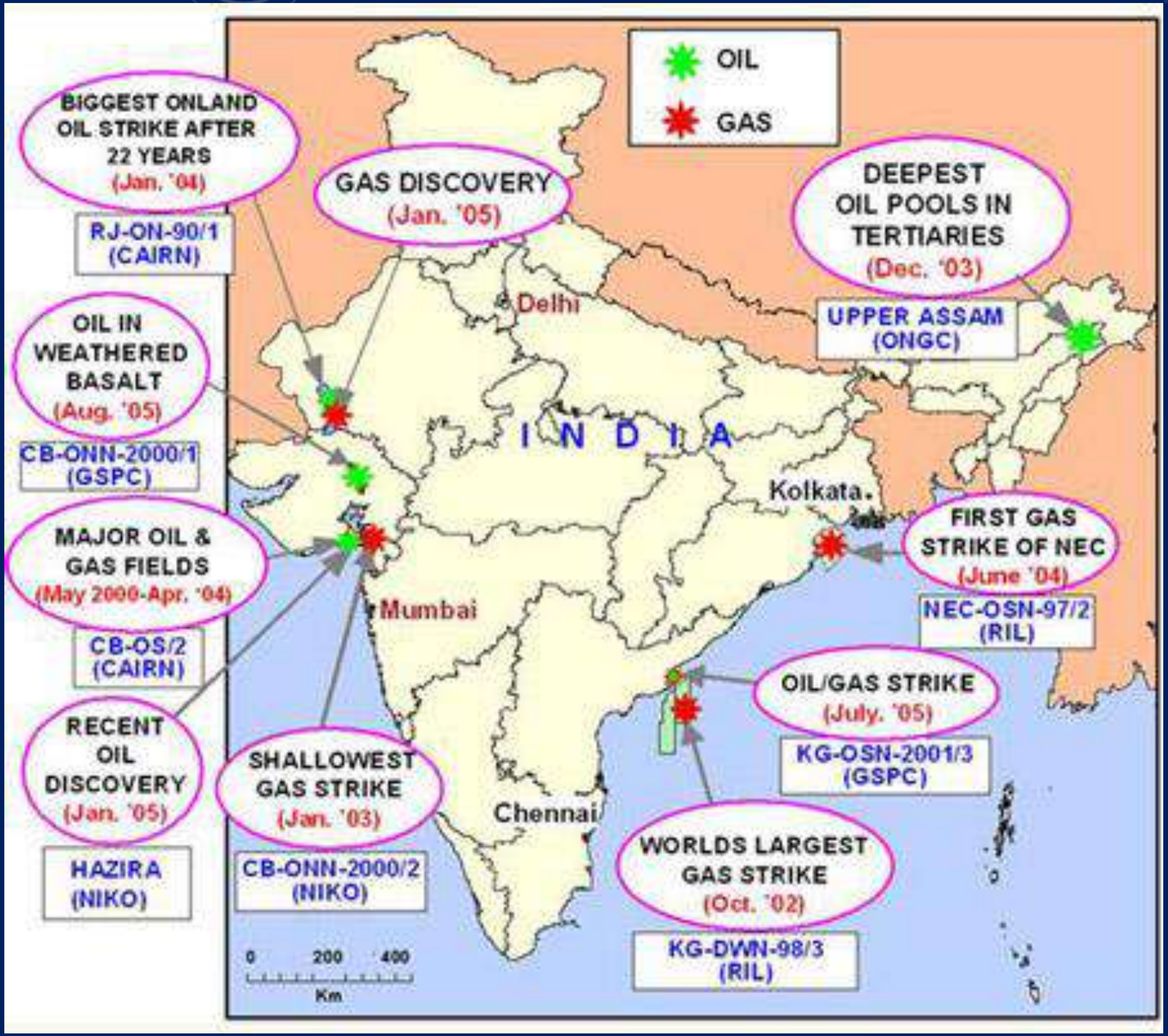
1250 Billion barrels

Source: M.K.Hubbert (1956) Shell

Ultimate US Oil Production



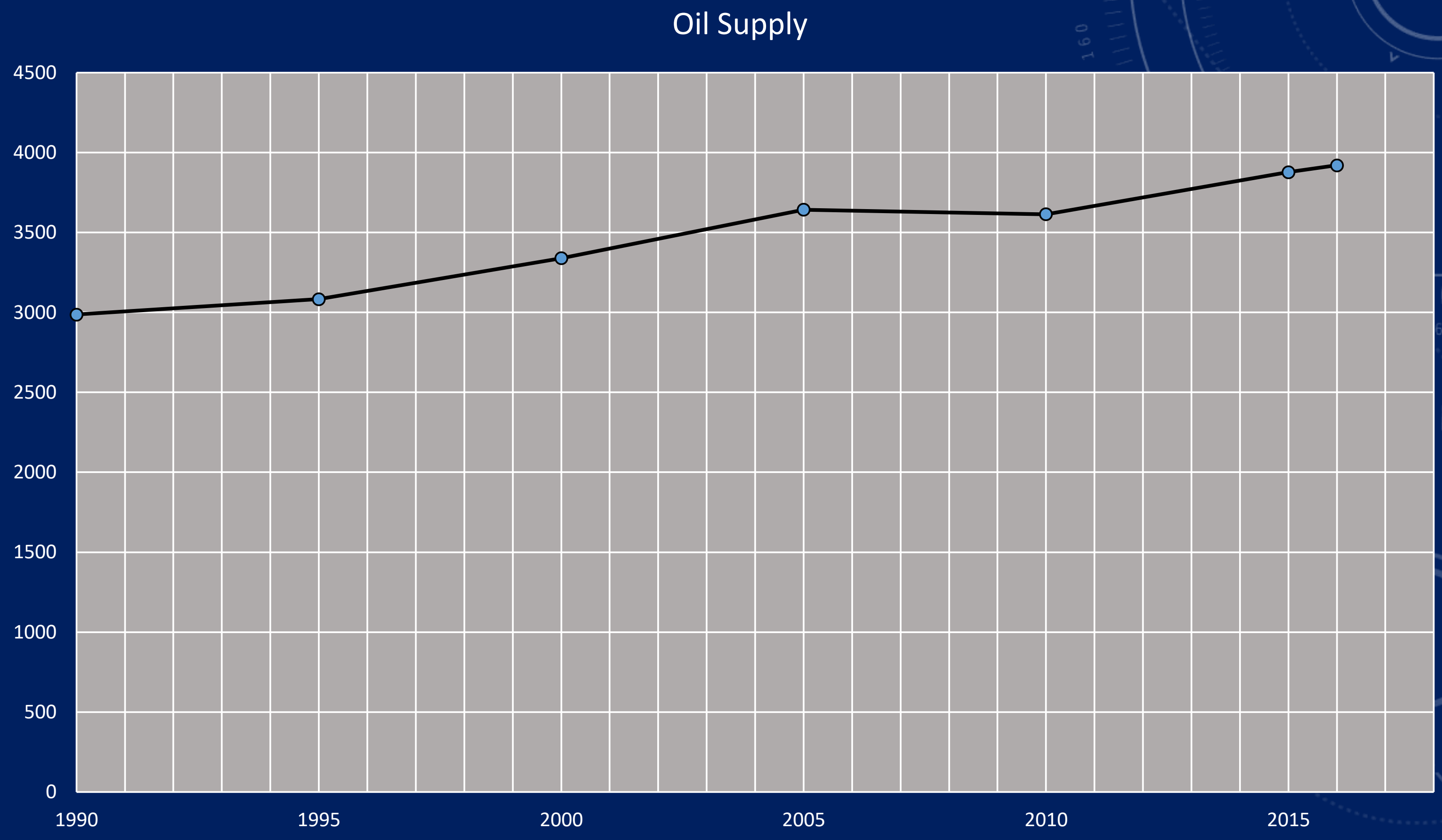
Source: M.K.Hubbert (1956) Shell



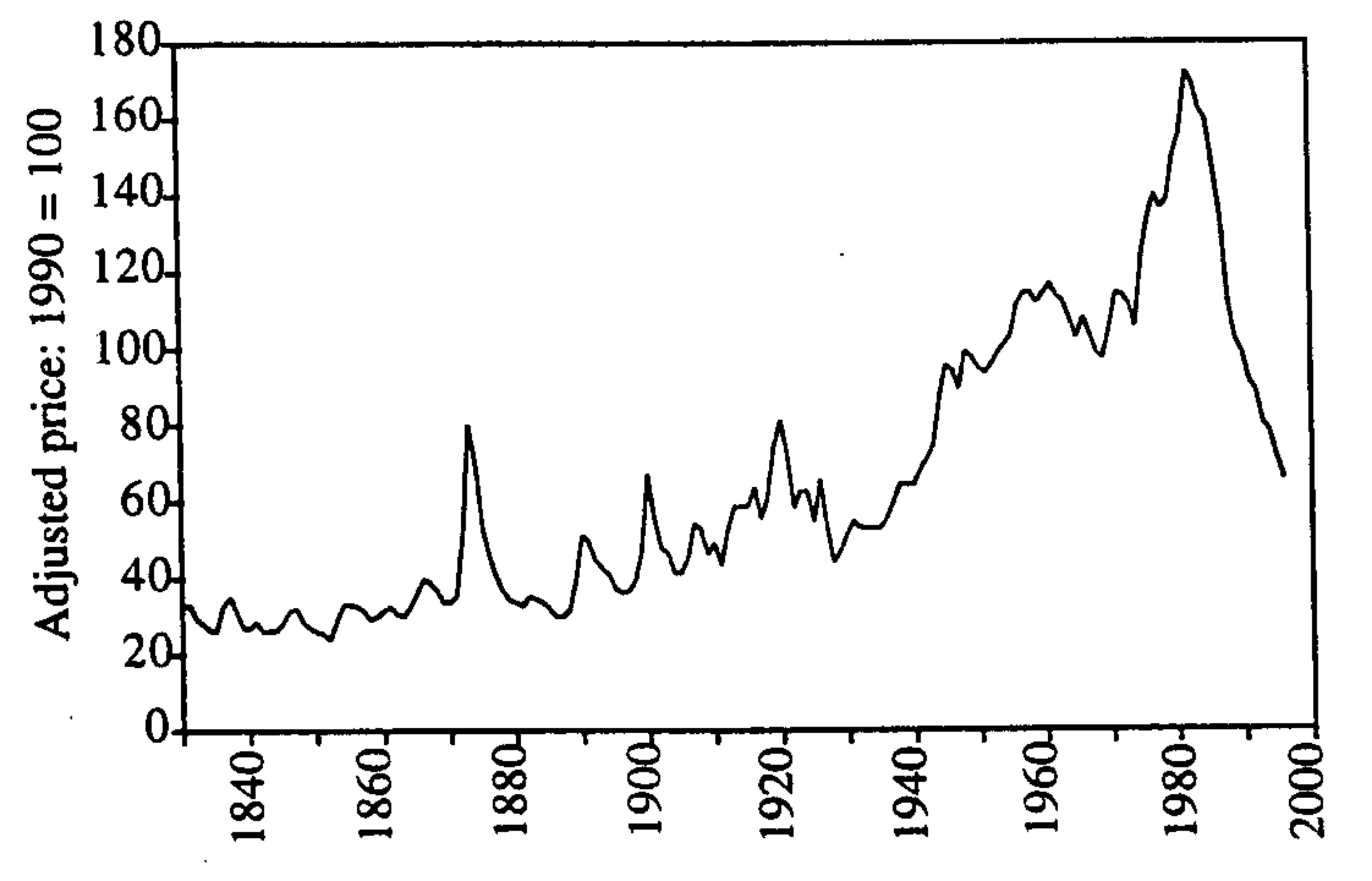
http://www.geologydata.info/images/mineral_fuel/petroleum_05.jpg

Global oil supply

1990	2987
1995	3083
2000	3339
2005	3643
2010	3614
2015	3878
2016	3921

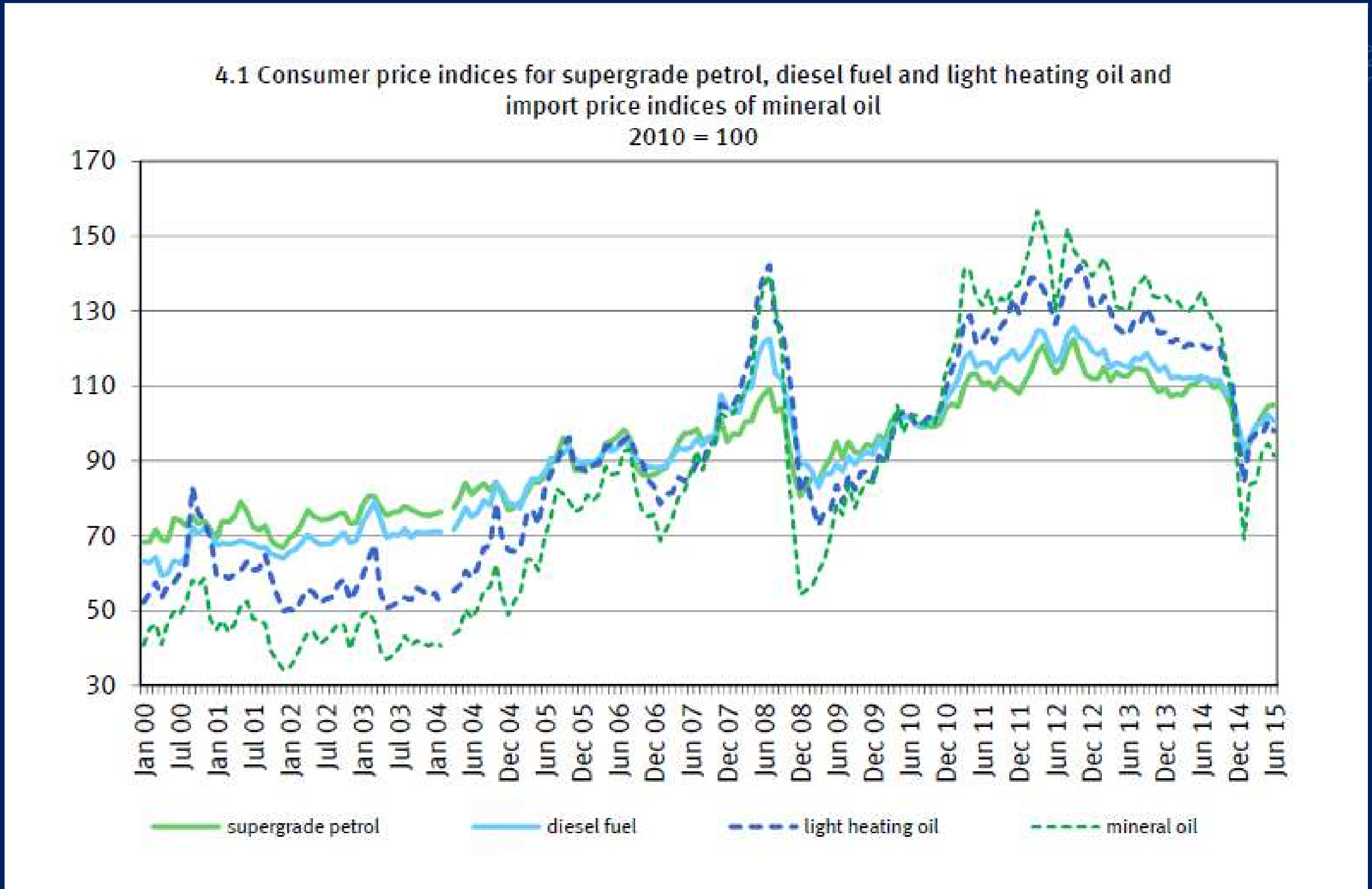


Coal Price Trend UK



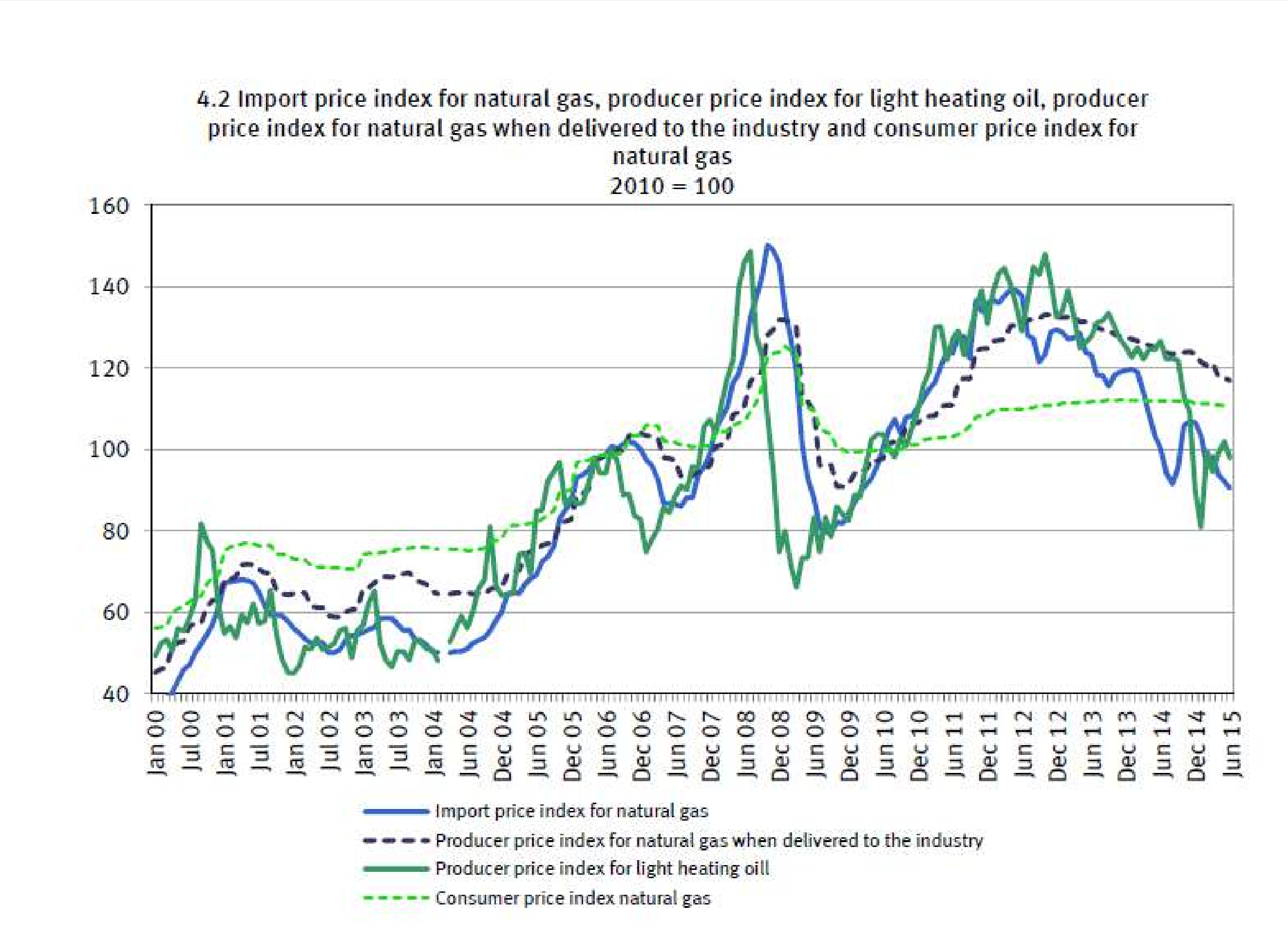
McCabe 1998

Price Variations (Germany)



https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/EnergyPriceTrendsPDF_5619002.pdf?__blob=publicationFile

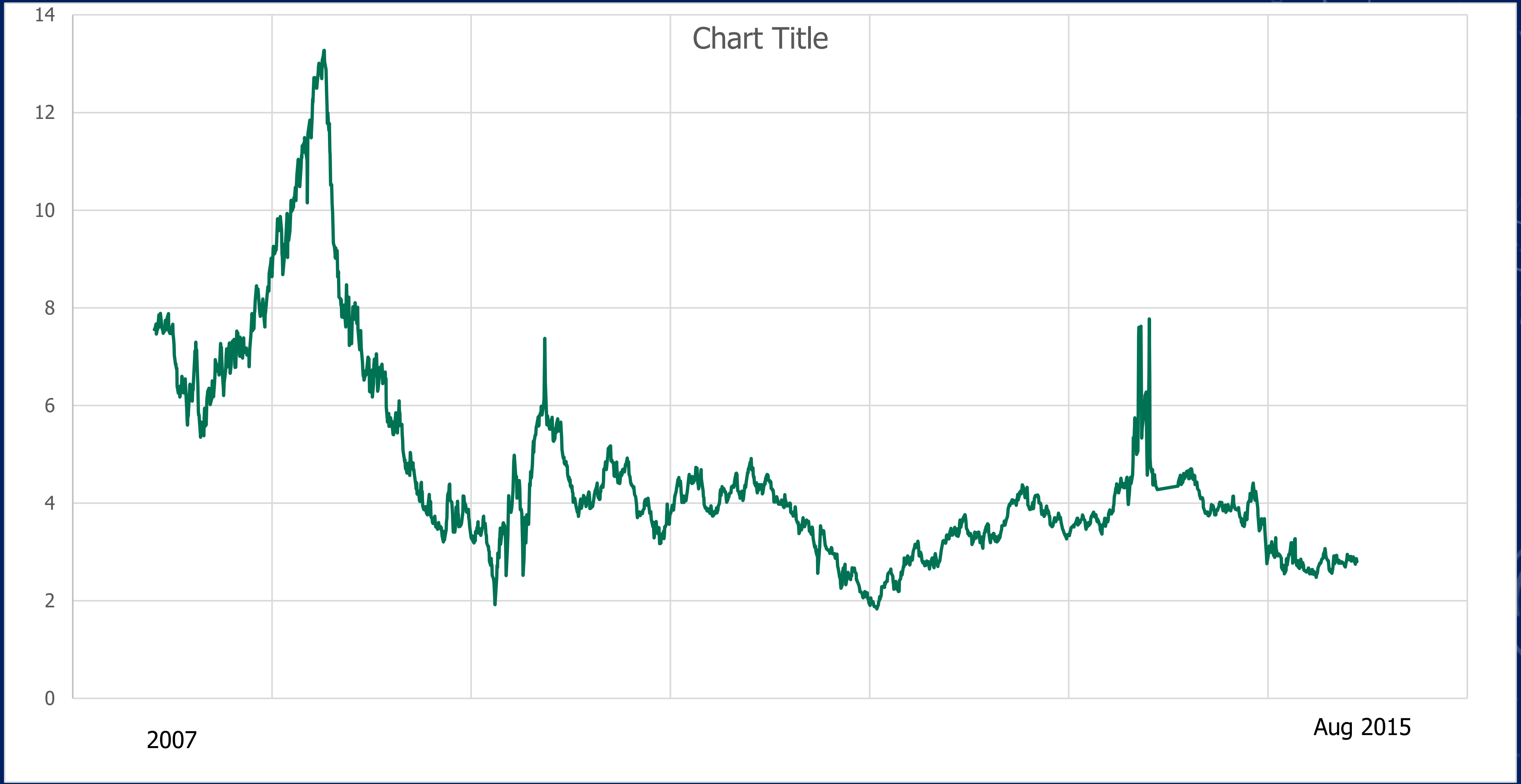
Price Variations (Ngas- Germany)



https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Energiepreise/EnergyPriceTrendsPDF_5619002.pdf?__blob=publicationFile

Henry Hub N Gas prices

$/MMBTU



https://www.quandl.com/collections/markets/natural-gas

US Coal Prices

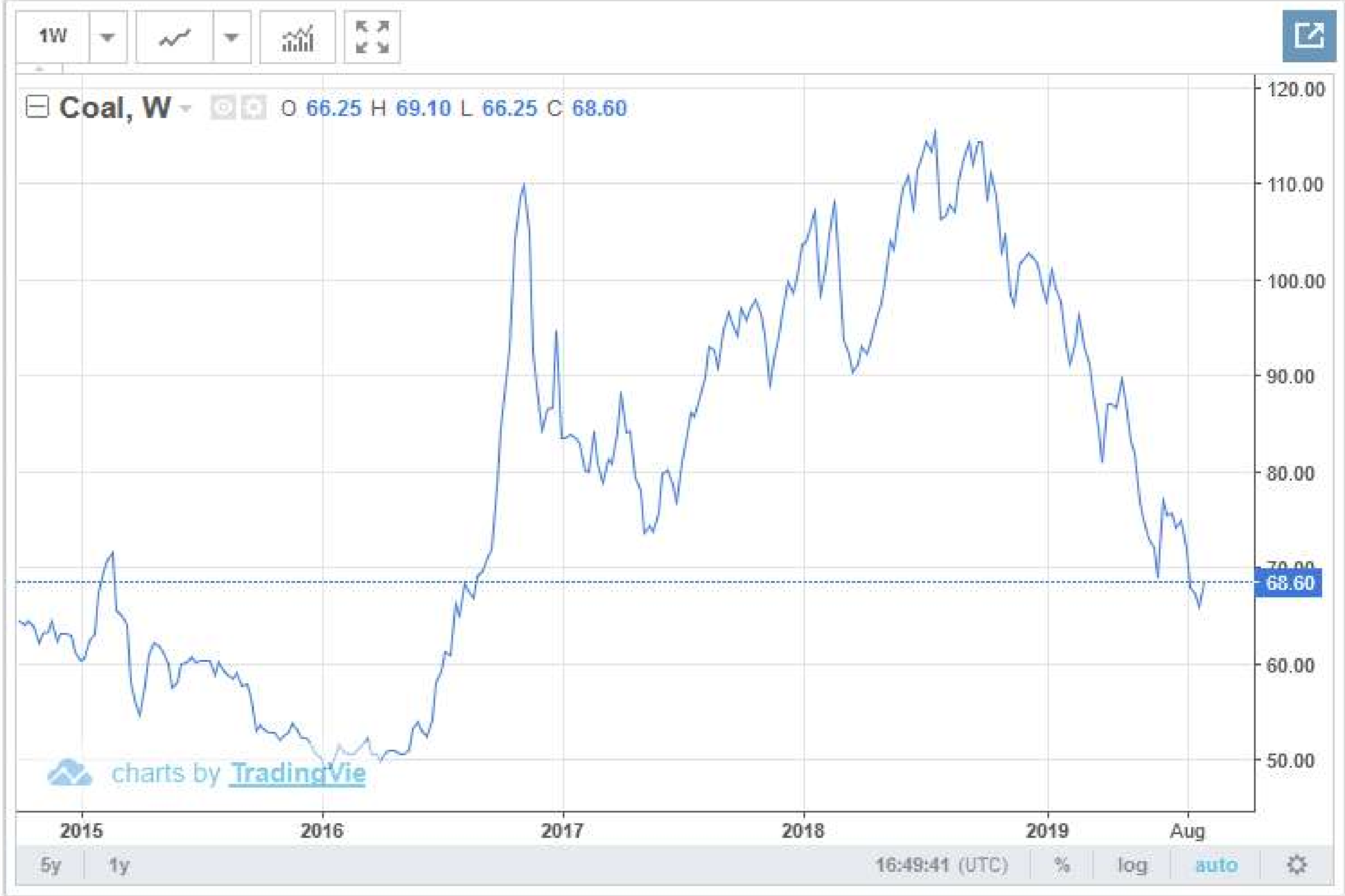
$/short tonne

https://www.quandl.com/collections/markets/coal

Australian coal Price

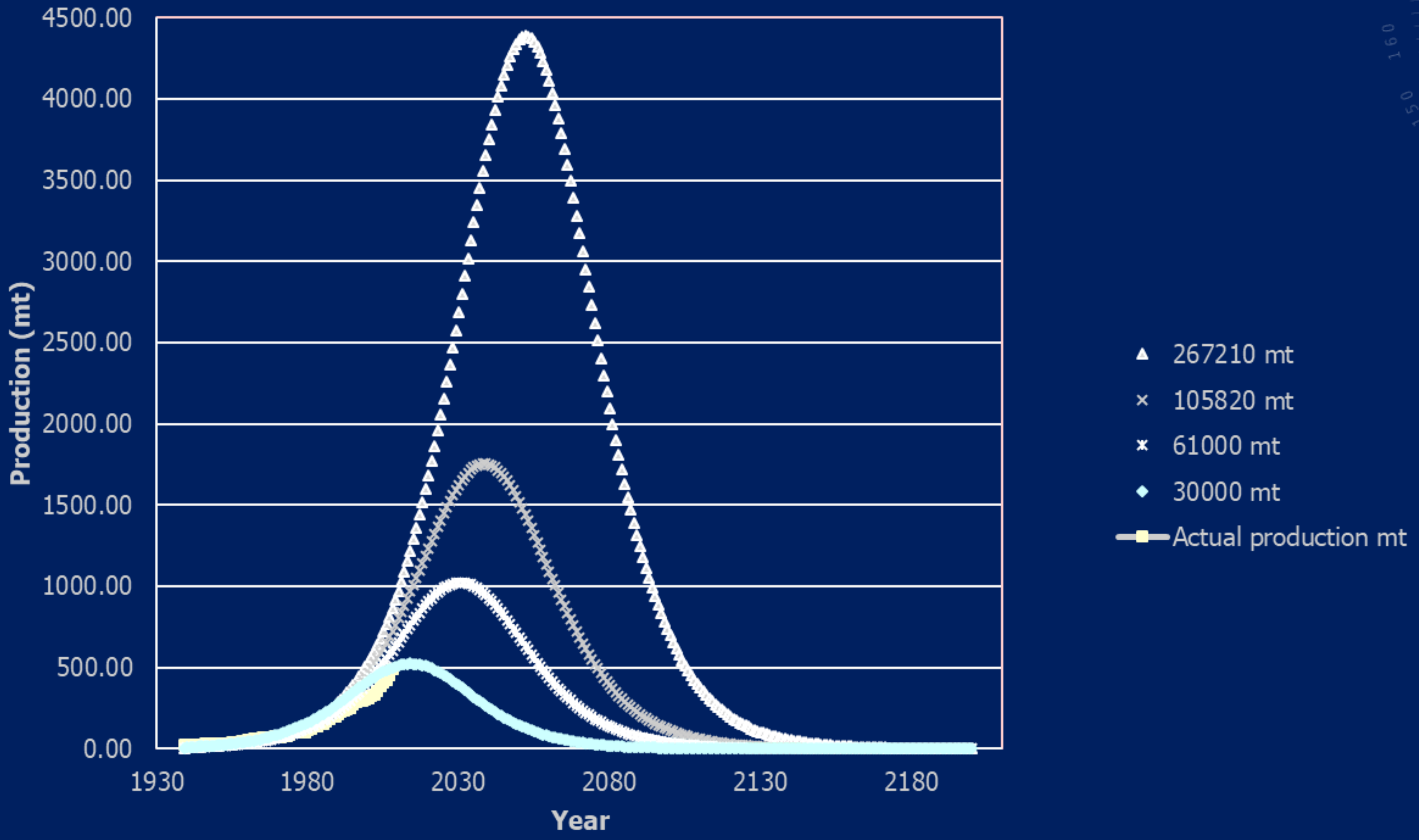
$/ metric tonne

https://www.quandl.com/collections/markets/coal

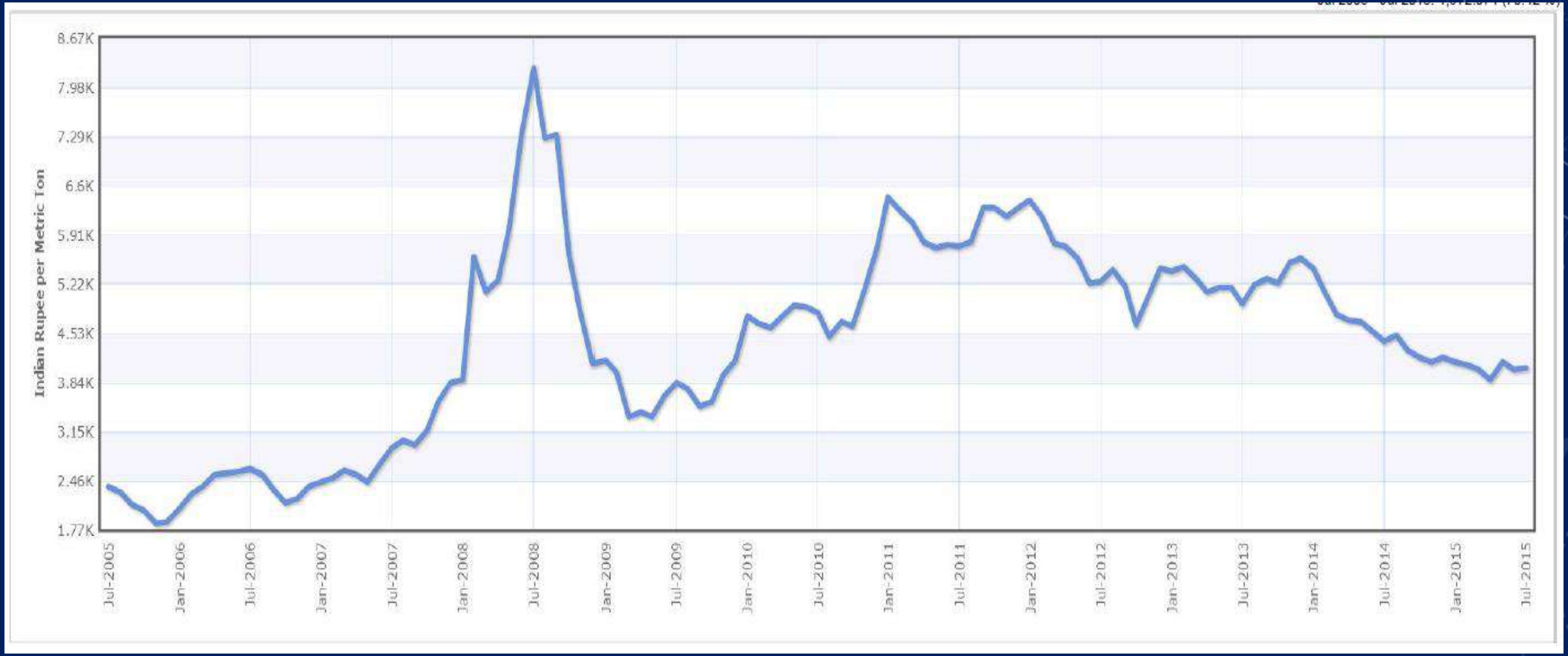


https://tradingeconomics.com/commodity/coal

Coal – Hubbert Analysis - India

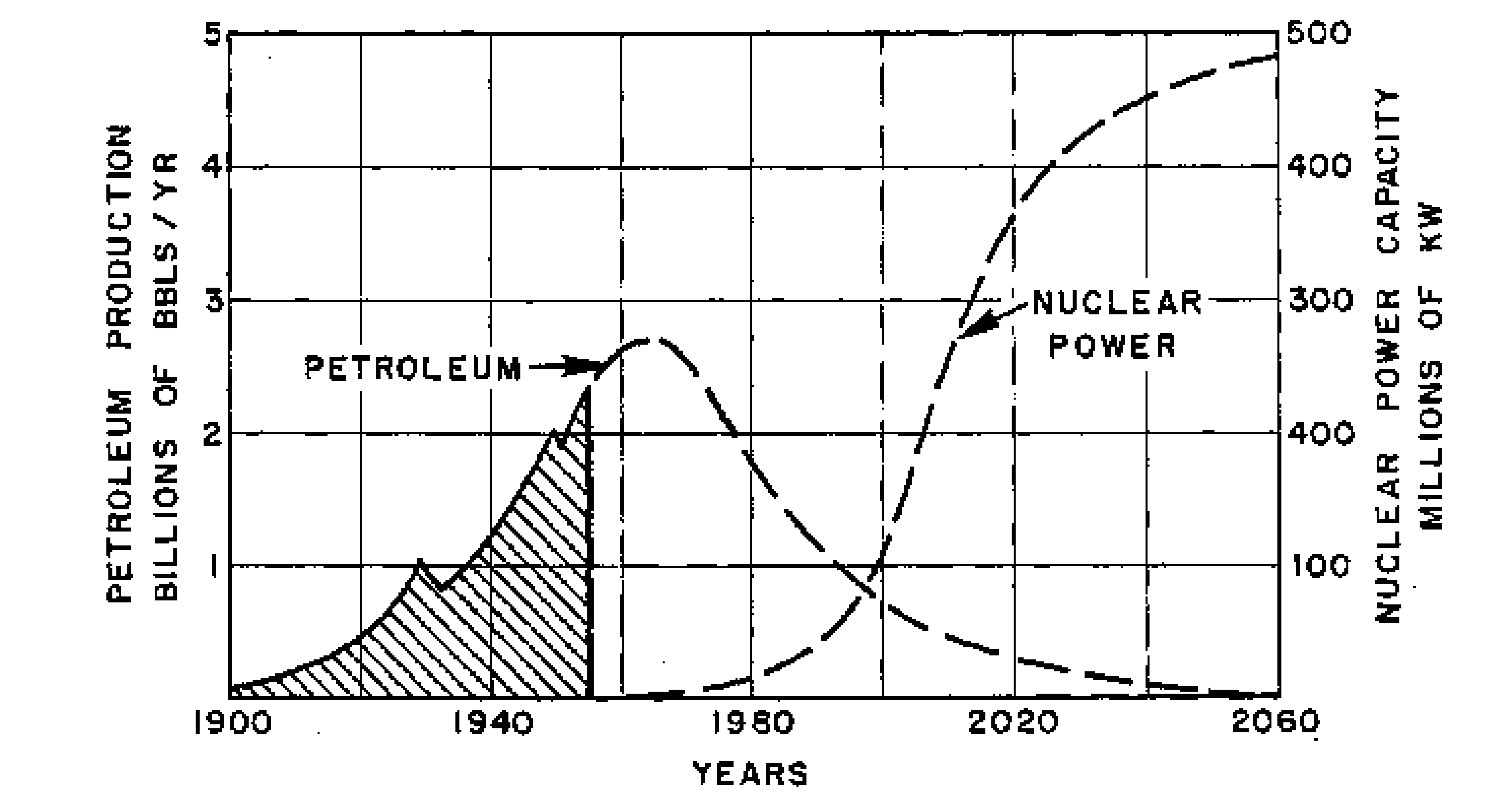


Imported Coal Price

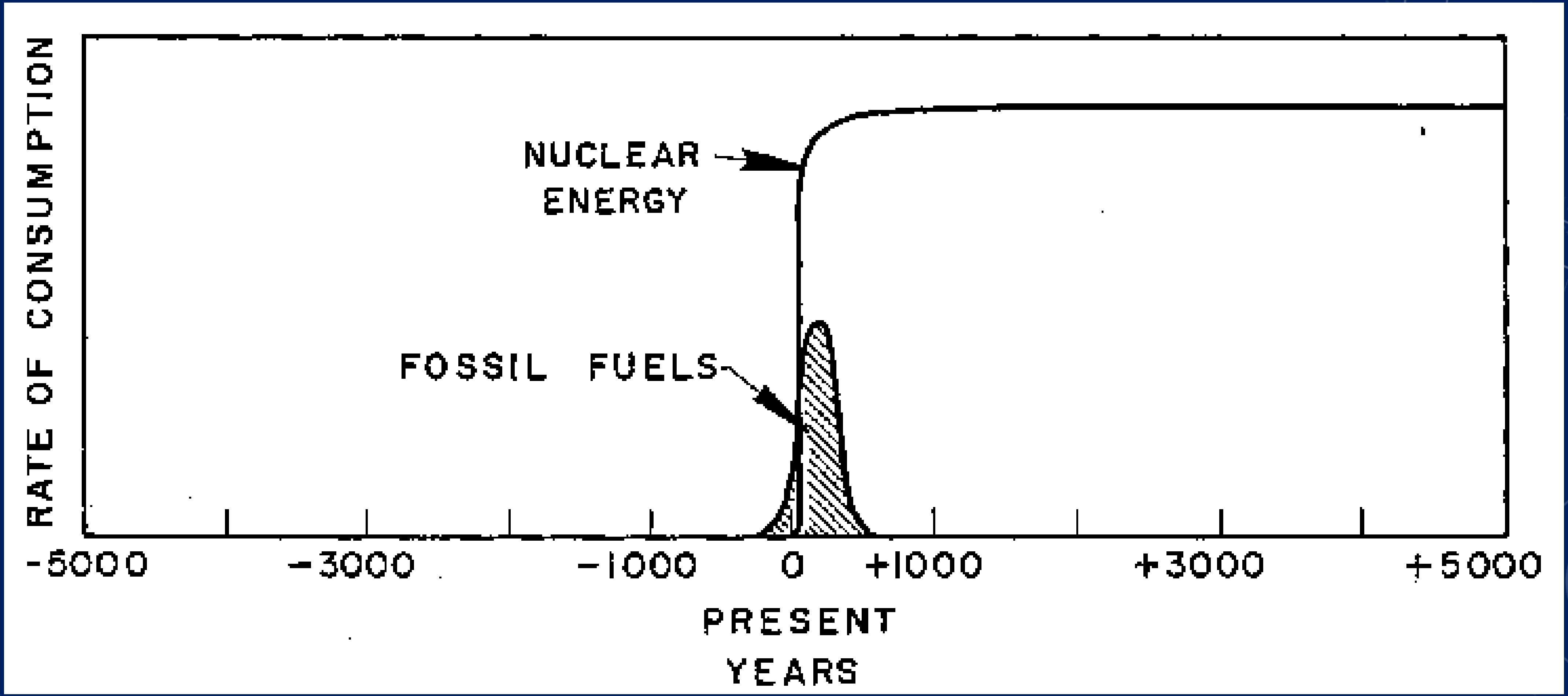


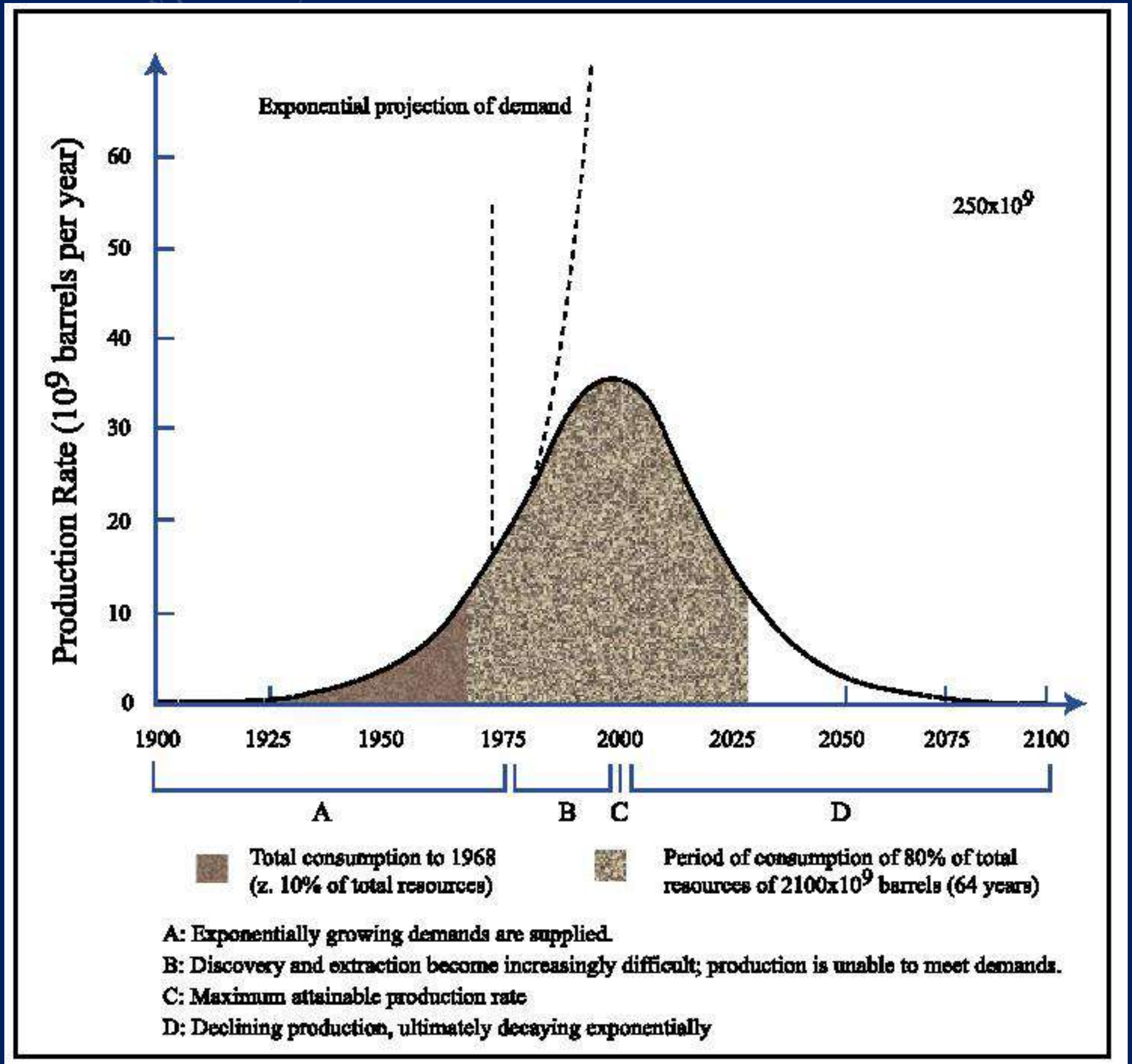
http://www.indexmundi.com/commodities/?commodity=coal-ustralian&months=120&currency=inr

Hubbert

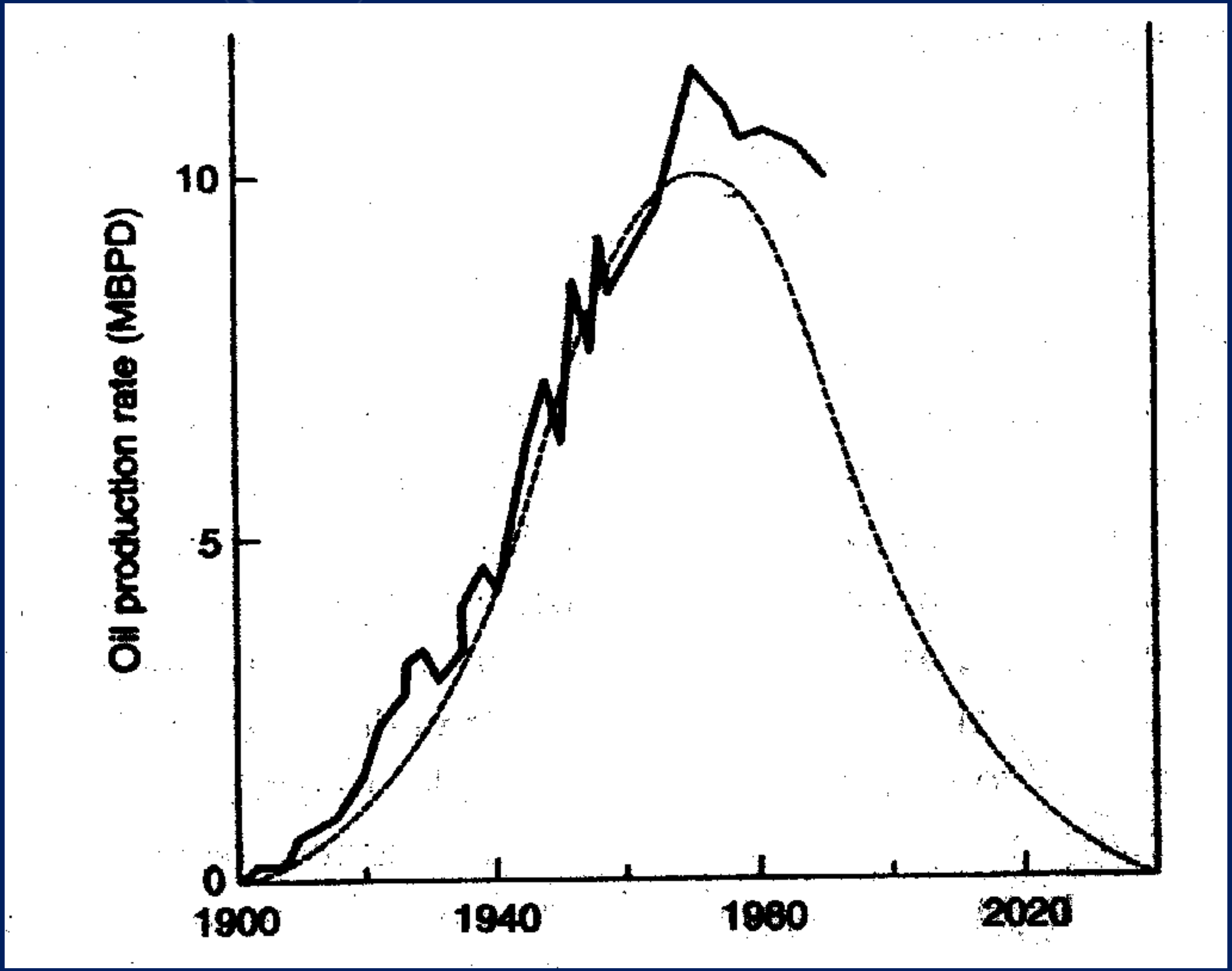


5
4
3
2
1
500
400
300
400
100
PETROLEUM PRODUCTION
BILLIONS OF BBLS / YR
NUCLEAR POWER CAPACITY
MILLIONS OF KW
PETROLEUM
NUCLEAR
POWER
1900
1940
1980
2020
2060
YEARS


RATE OF CONSUMPTION
NUCLEAR ENERGY
FOSSIL FUELS
-5000
-3000
-1000
0
+1000
+3000
+5000
PRESENT
YEARS



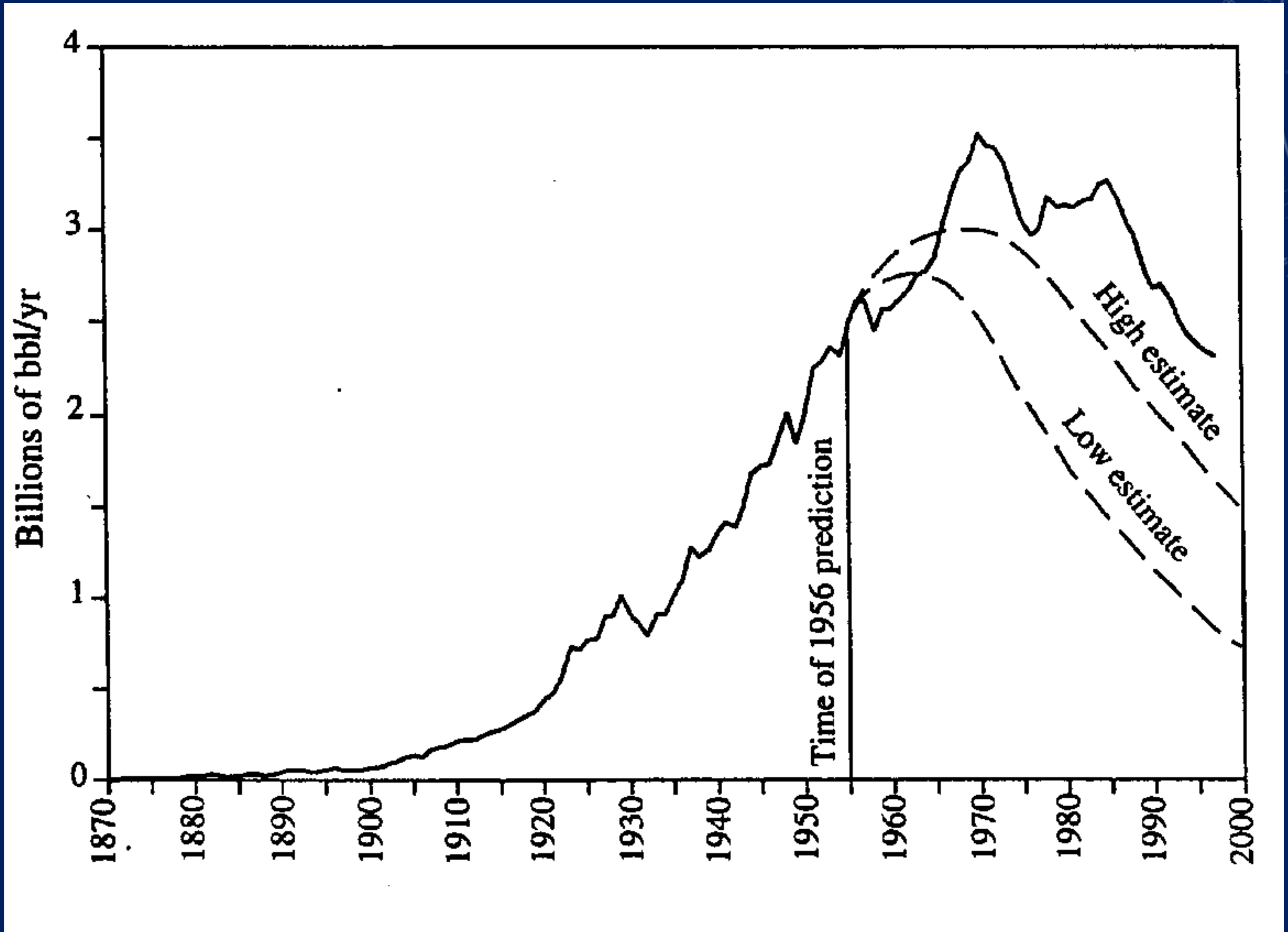
Source: MIT OCW



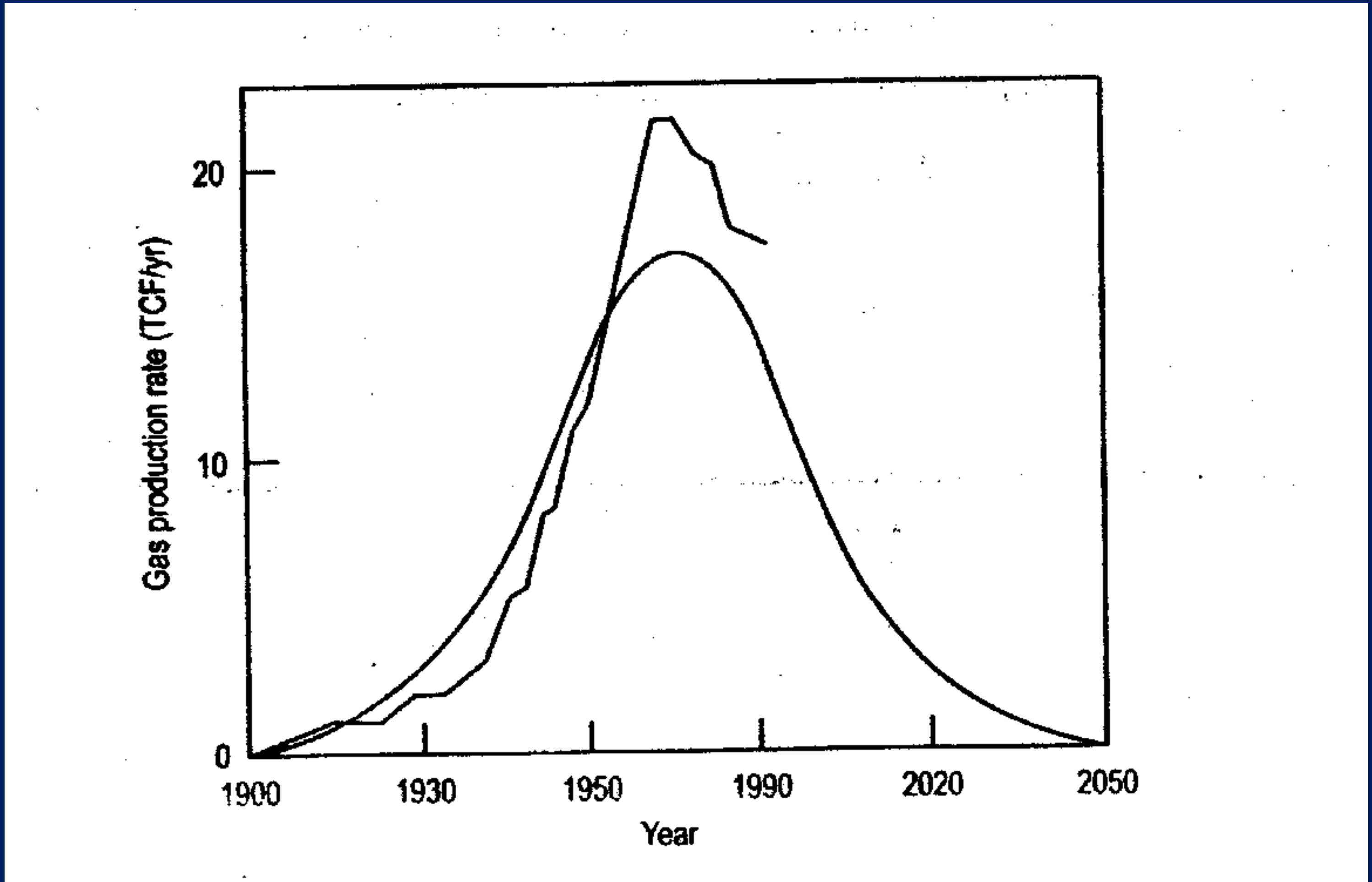
Comparison of an estimated Hubbert production curve for crude oil in the US with actual crude oil production data for the period 1900-1983

Source: Sustainable Energy (Tester et al, 2005)

Hubbert US estimate

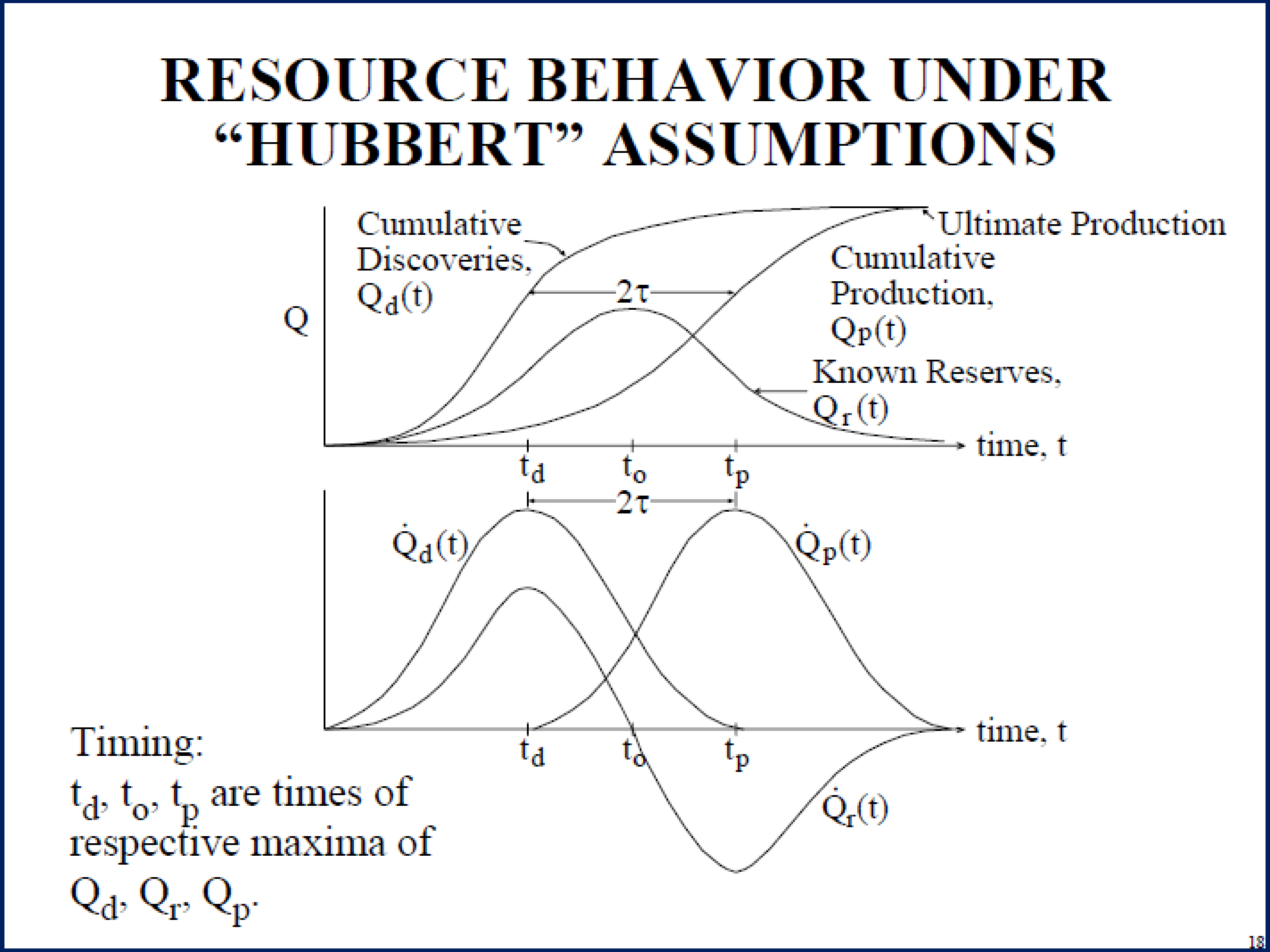


McCabe 1998

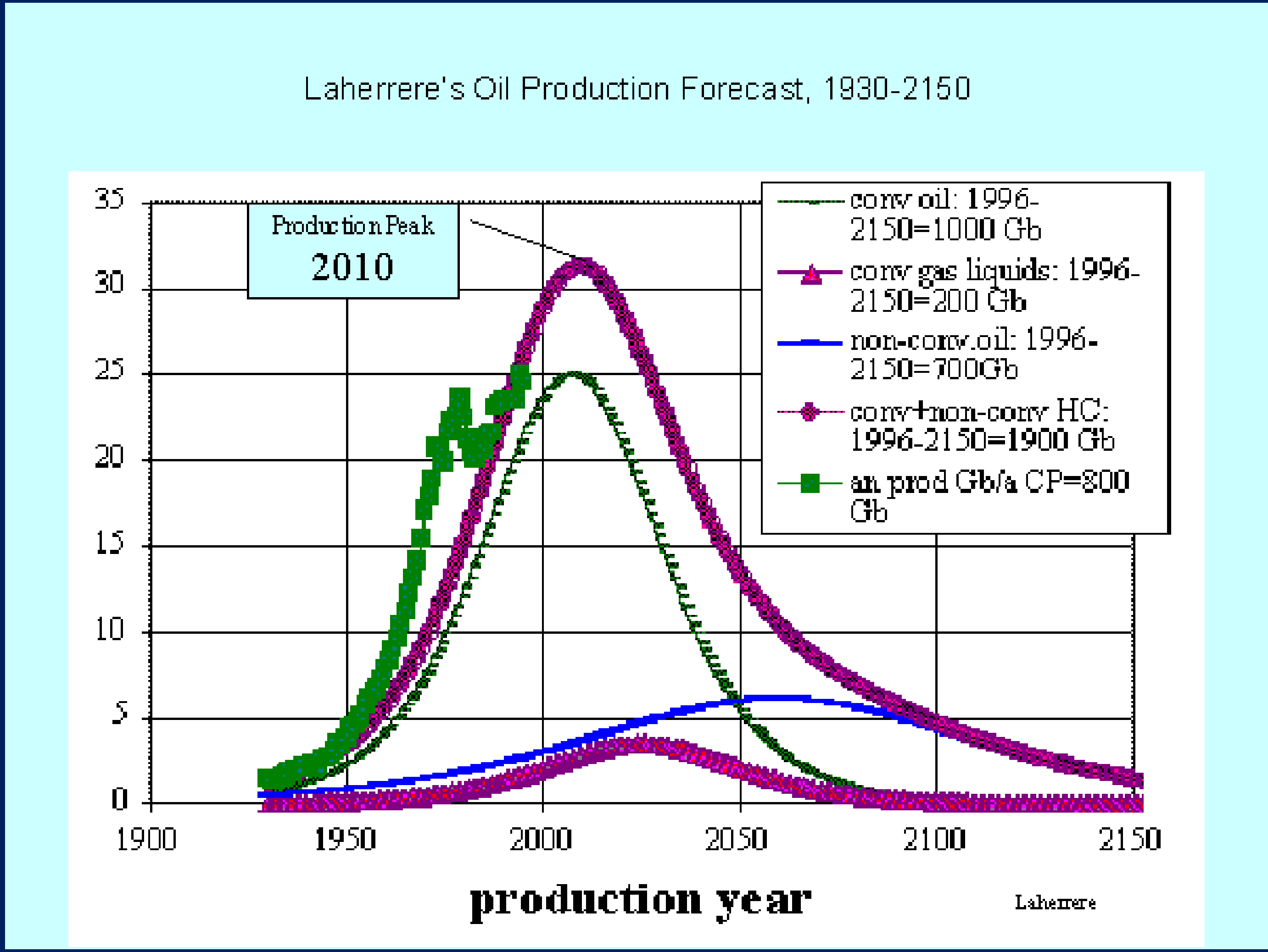


Comparison of an estimated Hubbert production curve for natural gas in the US with actual natural gas production data for the period 1900-1983

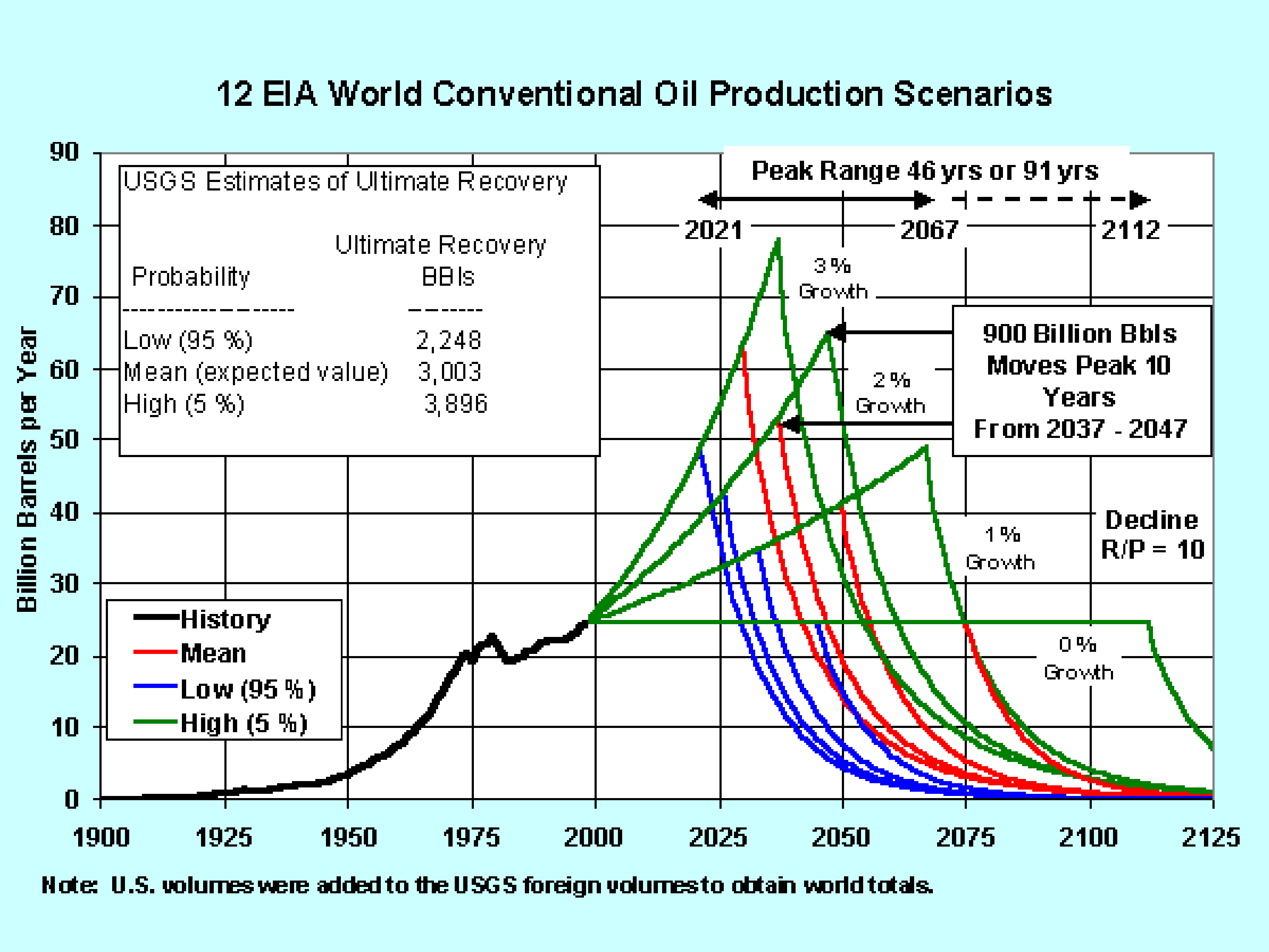
Source: Sustainable Energy (Tester et al, 2005)



Source: Sustainable Energy (Tester et al, 2005) MIT OCW



Source: www.eia.doe.gov Wood and Long,2000



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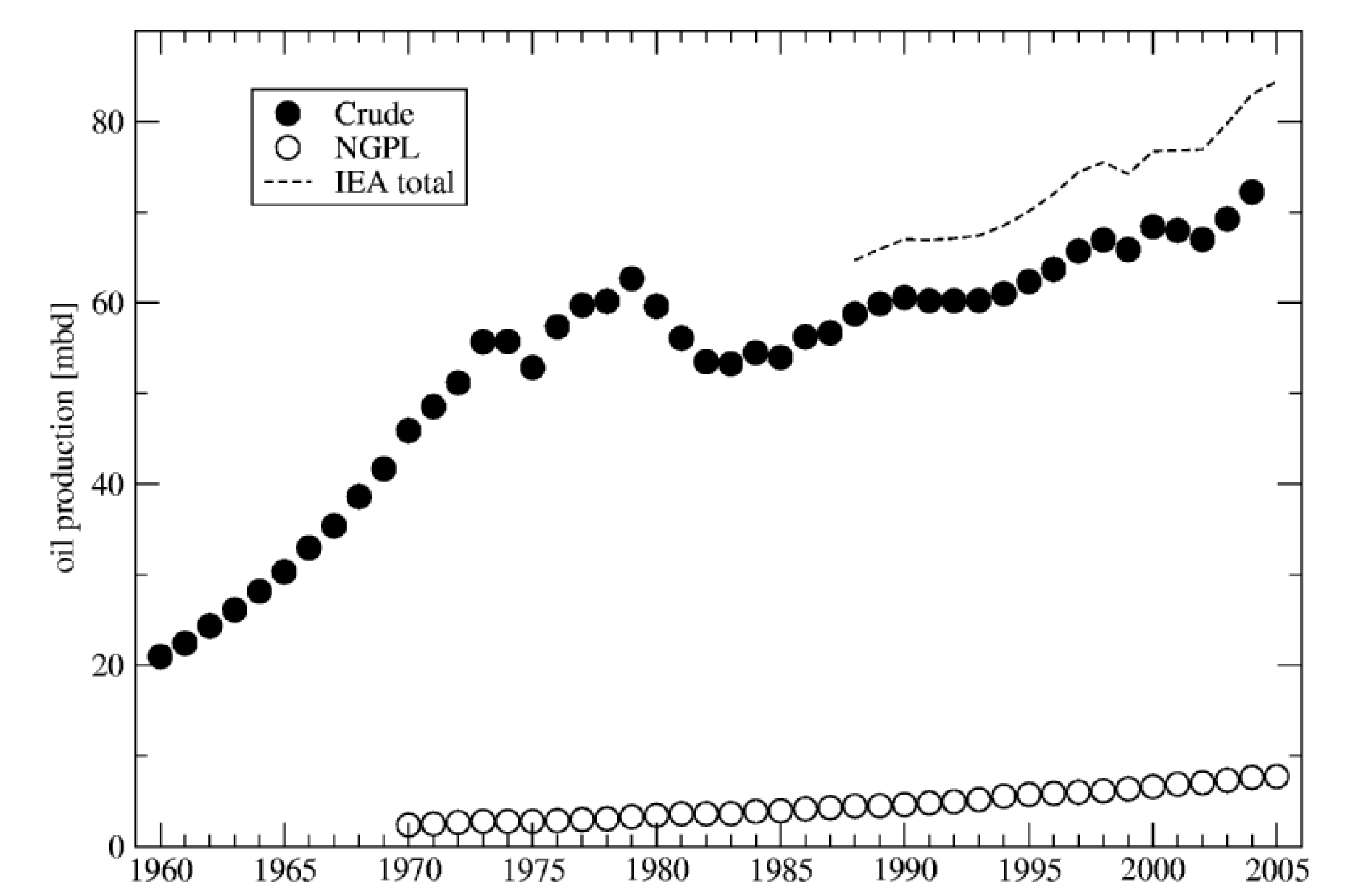


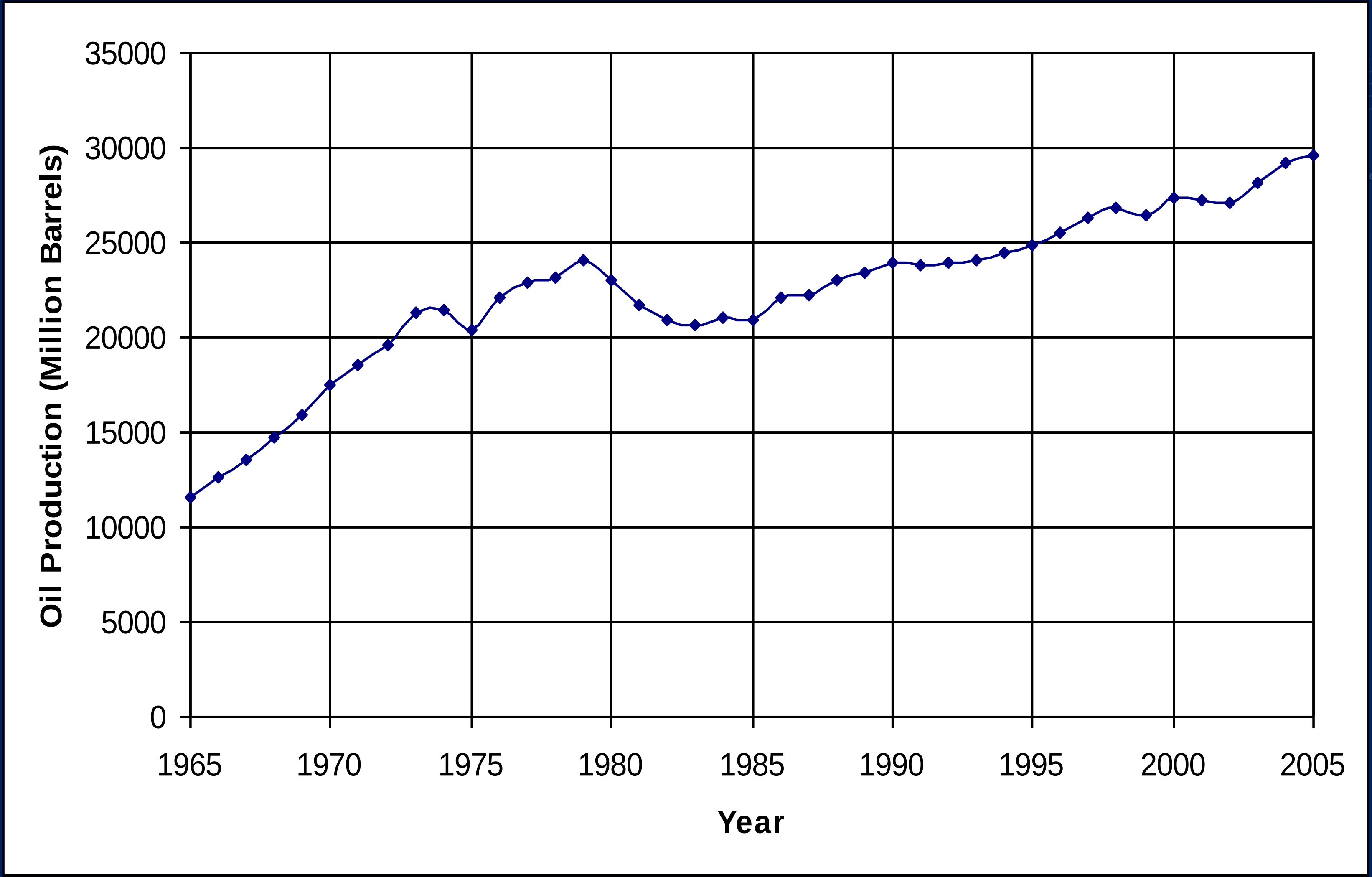
http://en.wikipedia.org/wiki/Image:Crude_NGPL_IEAtotal_1960-2004.png

Peak Oil Projections

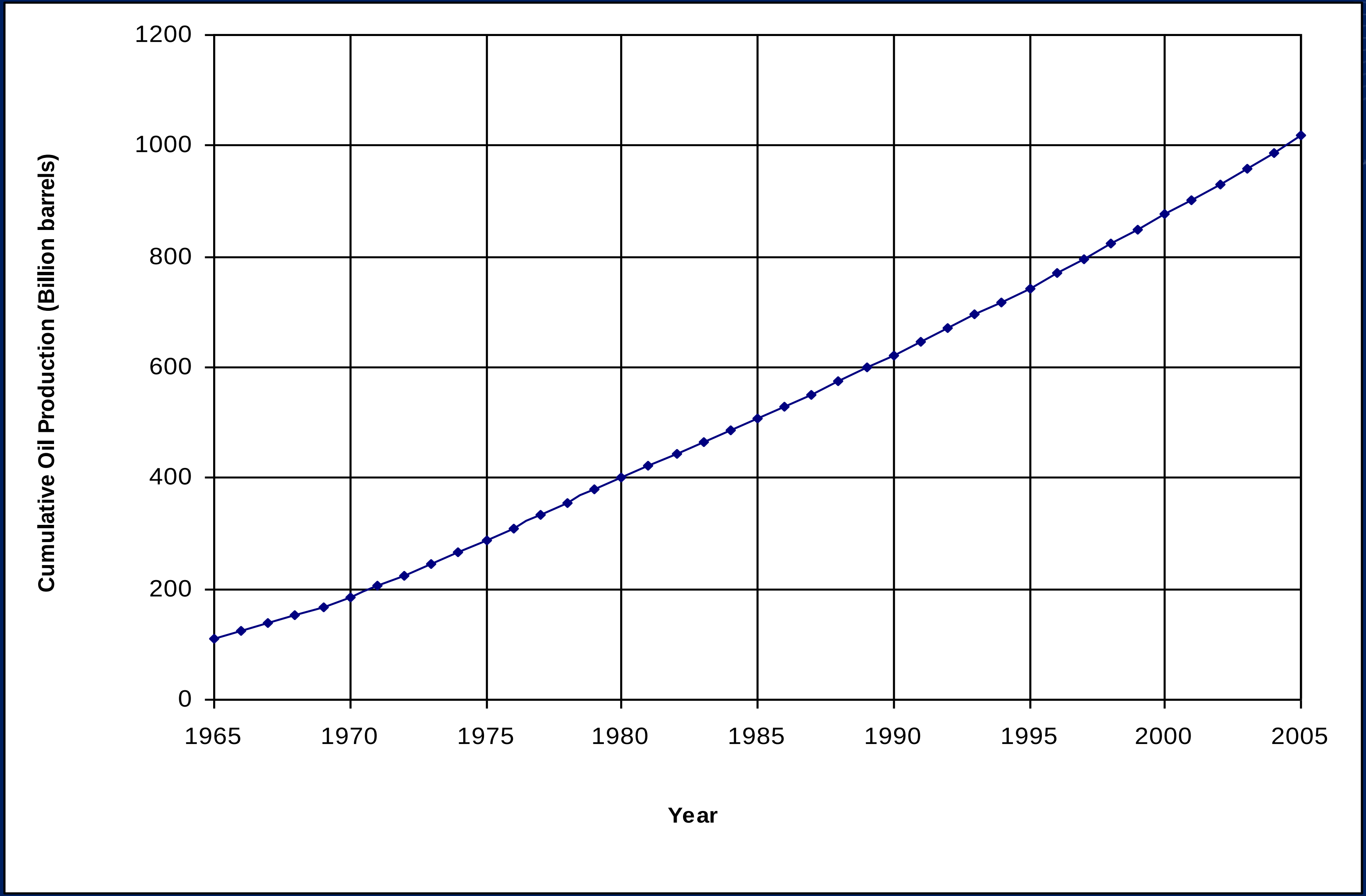
Projected Date	Source of Projection	Background & Reference
2006-2007	Bakhitari, A.M.S.	Oil Executive (Iran)[1]
2007-2009	Simmons, M.R.	Investment banker (U.S.) [2]
After 2007	Skrebowski, C.	Petroleum journal editor (U.K.) [3]
Before 2009	Deffeyes, K.S.	Oil company geologist (ret., U.S.)[4]
Before 2010	Goodstein, D.	Vice Provost, Cal Tech (U.S.) [5]
Around 2010	Campbell, C.J.	Oil geologist (ret., Ireland)[6]
After 2010	World Energy Council	World Non-Government Org.[7]
2012	Pang Xiongqi	Petroleum Executive (China)[8]
2010-2020	Laherrere, J.	Oil geologist (ret., France) [9]
2016	EIA nominal case	DOE analysis/ information (U.S.)[10]
After 2020	CERA	Energy consultants (U.S.) [11]
2025 or later	Shell	Major oil company (U.K.) [12]

Source : Hirsch (2005)

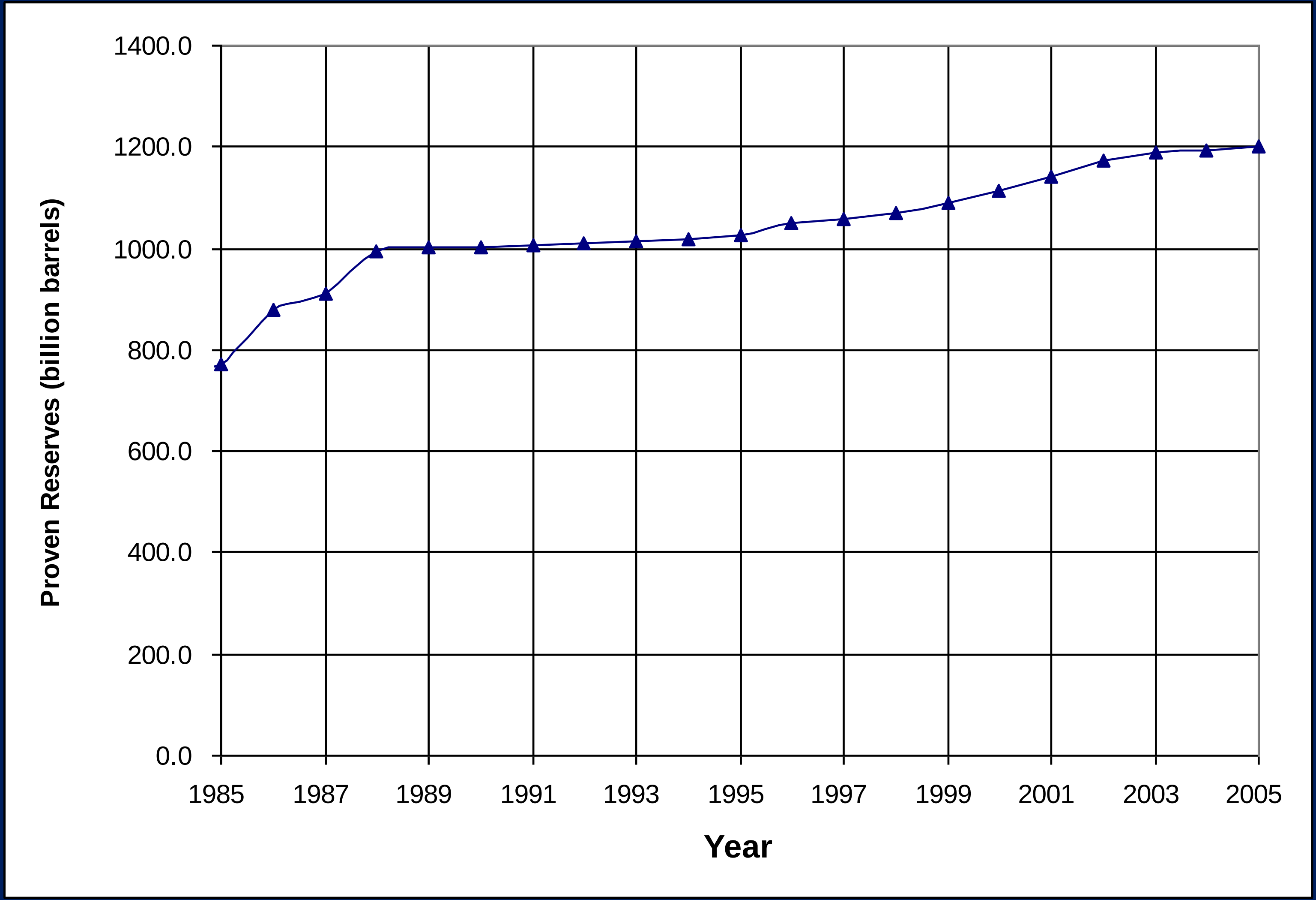
World Oil Production



Cumulative Production



Proven Reserves



Logistic Model

$$Q_P = \frac{Q_\infty}{1 + Ae^{-BQ_\infty t}}$$

$$\ln\left(\frac{Q_\infty}{Q_P} - 1\right) = \ln A - bt$$

$$b = BQ_\infty$$

$$P = \frac{dQ_P}{dt} = BQ_P(Q_\infty - Q_P)$$

$$\frac{dP}{dt} = 0, \text{point of inflection} \quad \frac{d^2Q_P}{dt^2} = 0$$

$$\frac{d^2Q_P}{dt^2} = B\frac{dQ_P}{dt}(Q_\infty - Q_P) + BQ_P\left(\frac{-dQ_P}{dt}\right) = 0$$

$$B \neq 0 \;, \frac{dQ_P}{dt} = P_m \neq 0$$

$$Q_\infty - Q_P - Q_P = 0$$

$$Q_P = \frac{Q_\infty}{2}$$

$$\frac{Q_\infty}{2} = \frac{Q}{1 + Ae^{-BQ_\infty t_m}}$$

$$2 = 1 + Ae^{-BQ_\infty t_m}$$

$$1 = Ae^{-BQ_\infty t_m}$$

$$\frac{1}{A} = e^{-BQ_\infty t_m}$$

$$-\ln A = -BQ_\infty t_m$$

$$t_m = \frac{\ln A}{BQ_\infty} = \frac{\ln\ A}{b}$$

Method

- Get time series data P(t)
- Assume starting value $Q_p(Ts)$
- $Q_p(t) = Q_p(t-1) + P(t)$ from Ts till recent
- Obtain estimate of Q_∞ from resource estimate
- Linear regression of ln $(Q_\infty / Q_p - 1)$ against time – get co-efficients A, B
- Find year of peaking

Hubbert Model – form

$$P = \frac{2P_M}{1 + \cosh[b(t - t_M)]}$$

$$U = 4P_M/b$$

Multi-Hubbert model

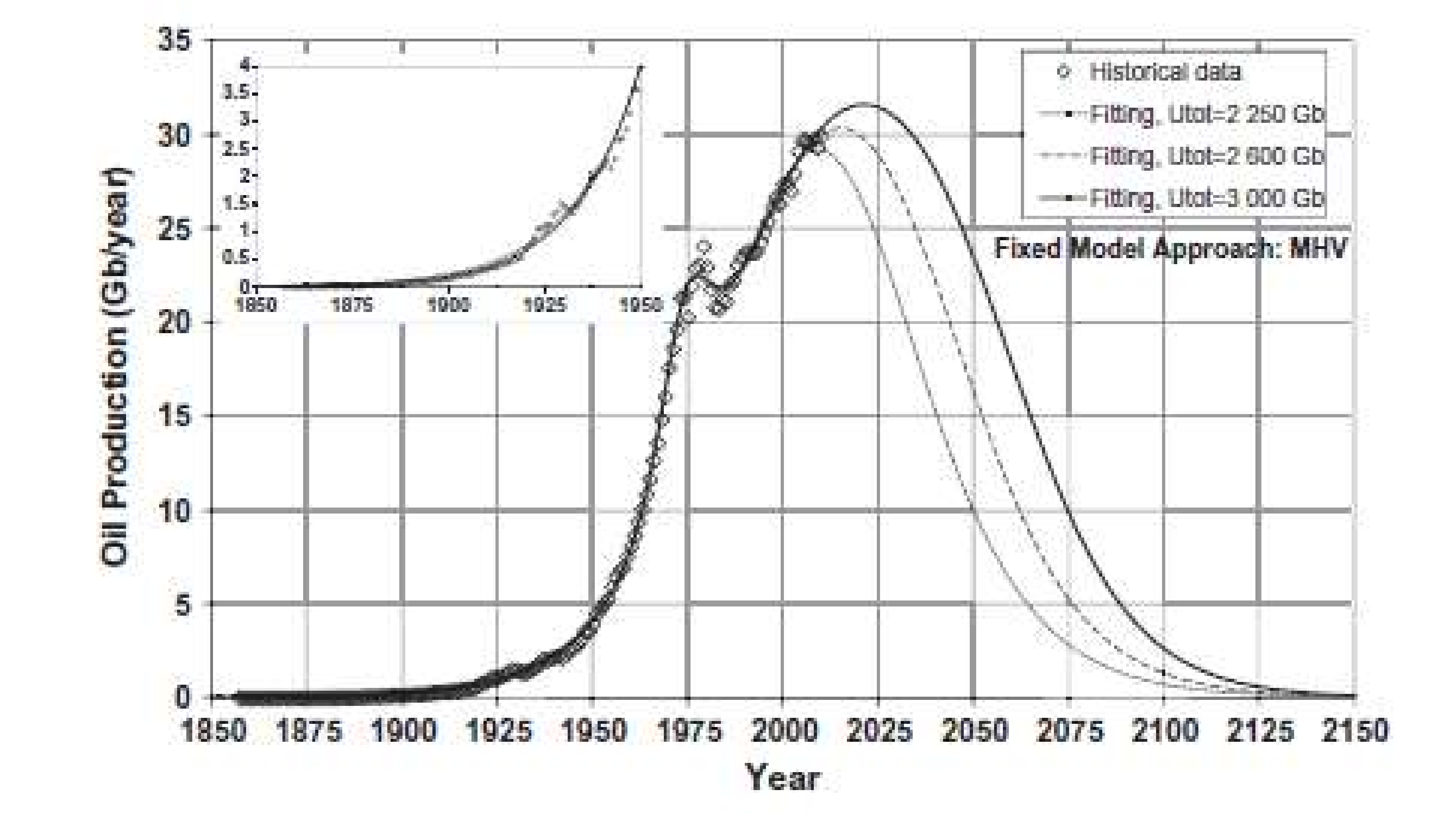
$$P = \sum_{i=1}^{N} \frac{2P_{M_i}}{1 + \cosh[b_i(t - t_{M_i})]}$$

N being the number of cycles, P_{M_i} for $i = 1, \ldots, N$ the peak production of each cycle, and t_{M_i} the corresponding peak year.

$$U_i = 4P_{M_i}/b_i$$

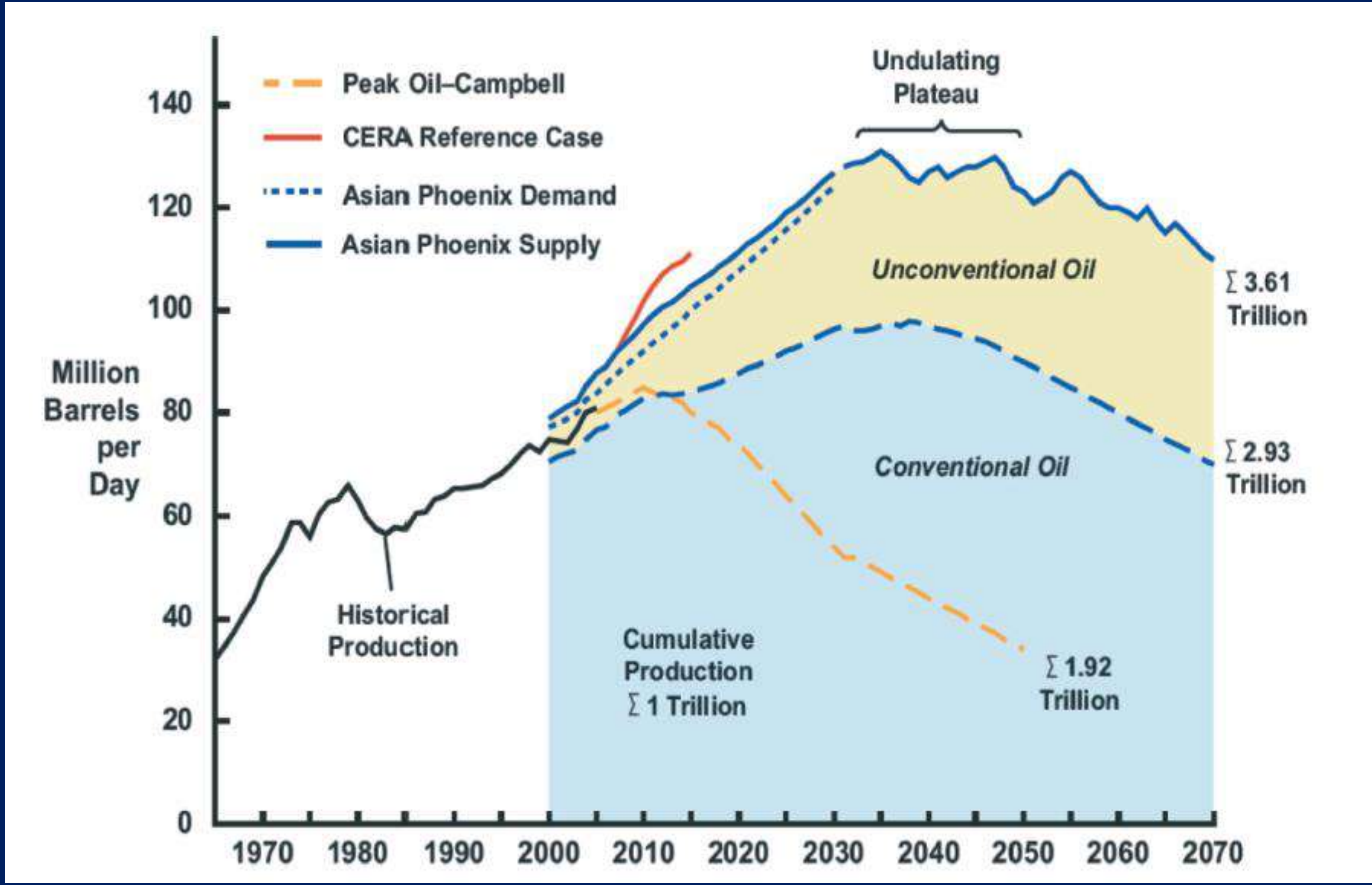
where b_i for $i = 1, \ldots, N$ are the slope of each cycle.

Fitting Multi-Hubbert Model



G. Maggio, G. Cacciola / Fuel 98 (2012)

Peak oil?



Source: GEA Chapter 7

Brazil – Oil Production

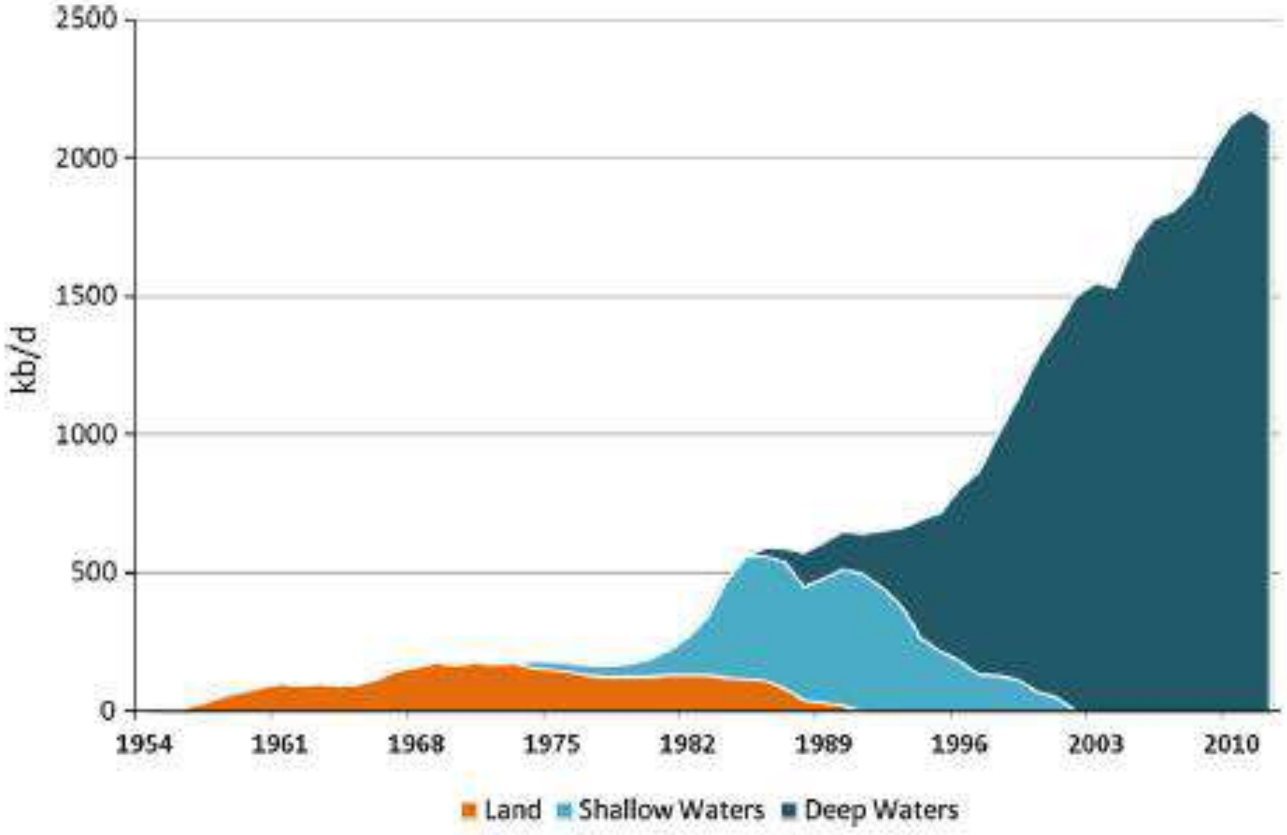
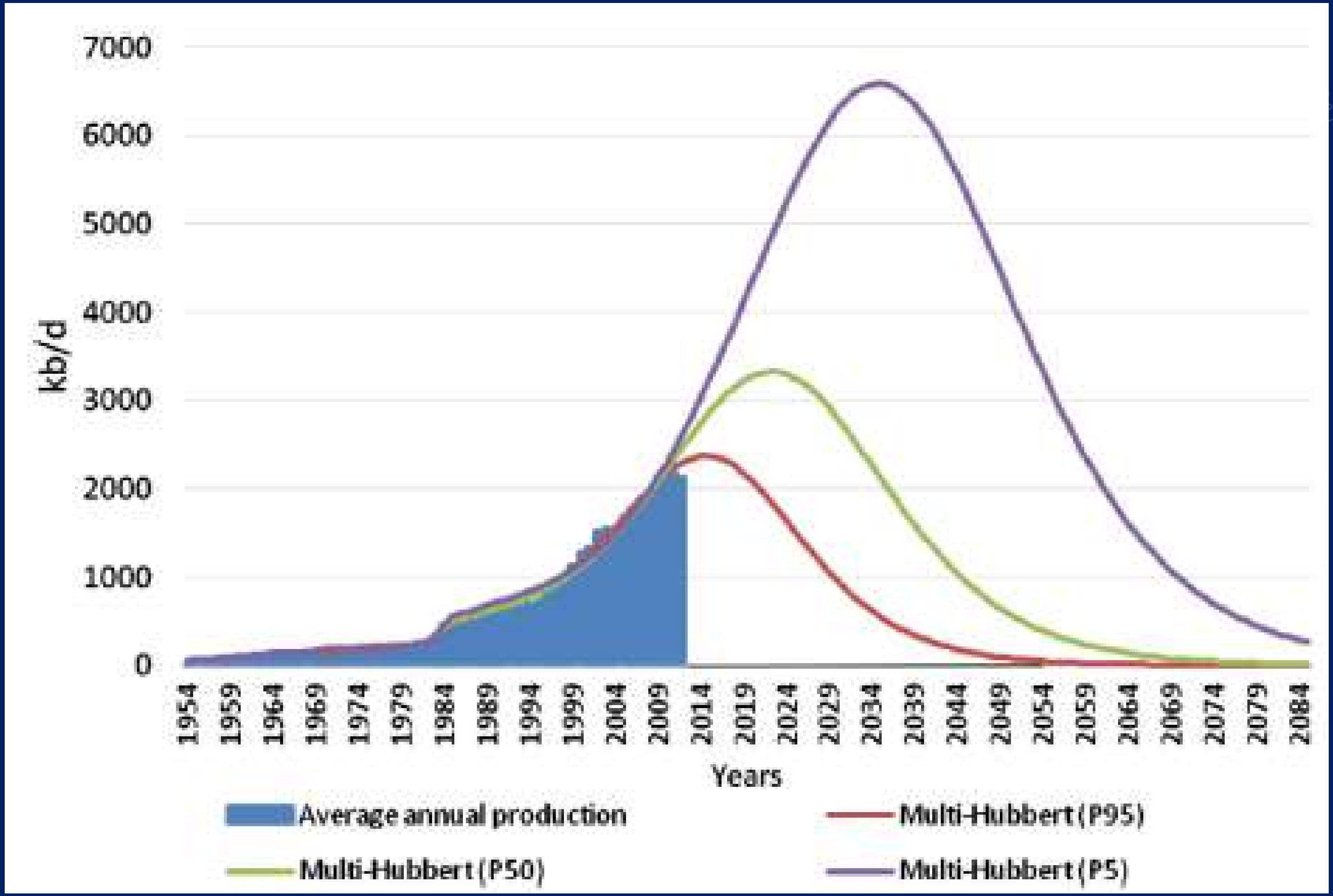


Fig. 1. Oil production by cycle (Mb/d) – Annual average of Brazil.

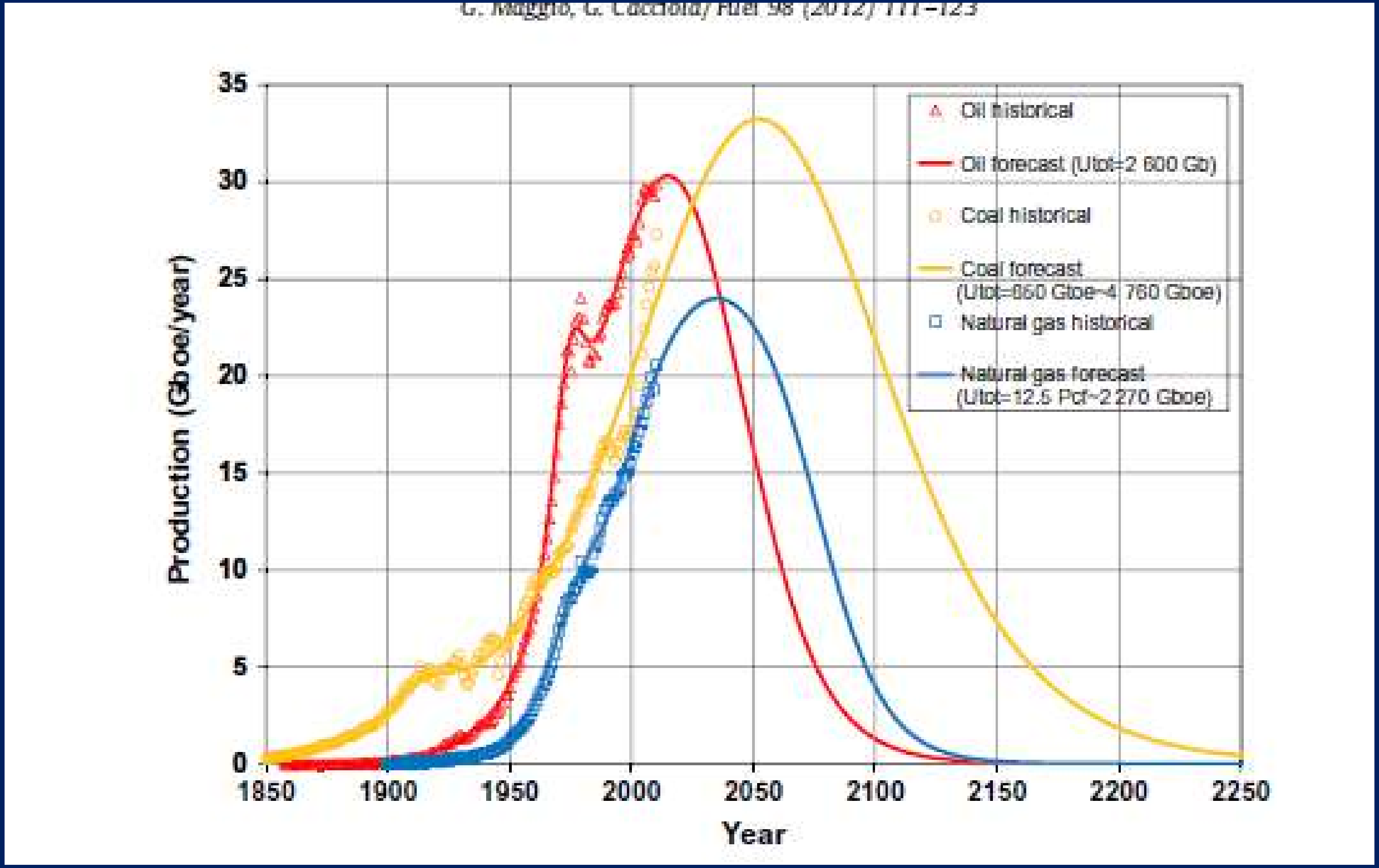
Saraiva et al, 2014, Fuel

Brazil- Multi Hubbert curves



Saraiva et al, 2014, Fuel

Fossil fuel reserves



G. Maggio, G. Cacciola/ Fuel 98 (2012)

Oil Drilling Technology

Reaching Deeper

Some of the innovations that have enabled oil output to increase almost continuously since the industry's dawn

1909 ▲ | Roller-cone drill bits are introduced, shortening time required to drill a well.

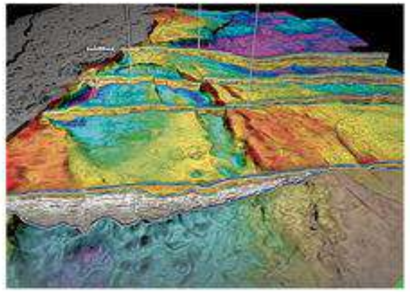
1929 | Directional drilling creates ability to point wells in a general direction.

1941 | A horizontal well, which begins vertically and then turns to run horizontally underground, is drilled in Azerbaijan.

1946 | Researchers successfully "frack" a well in southwestern Kansas. Within a few years, hydraulic-fracturing technology will be commercially available.

1949 ▲ | Offshore drilling begins in the shallows of the Gulf of Mexico.

1959 | Halliburton invents high-temperature cement, allowing wells to reach deeper.



1970 ▲ | Seismic imaging technology is used by Shell and Mobil to find "bright spots" deep under the Gulf of Mexico that indicate oil deposits.

1982 | 3-D seismic imaging is introduced, vastly improving the industry's ability to locate oil deposits.

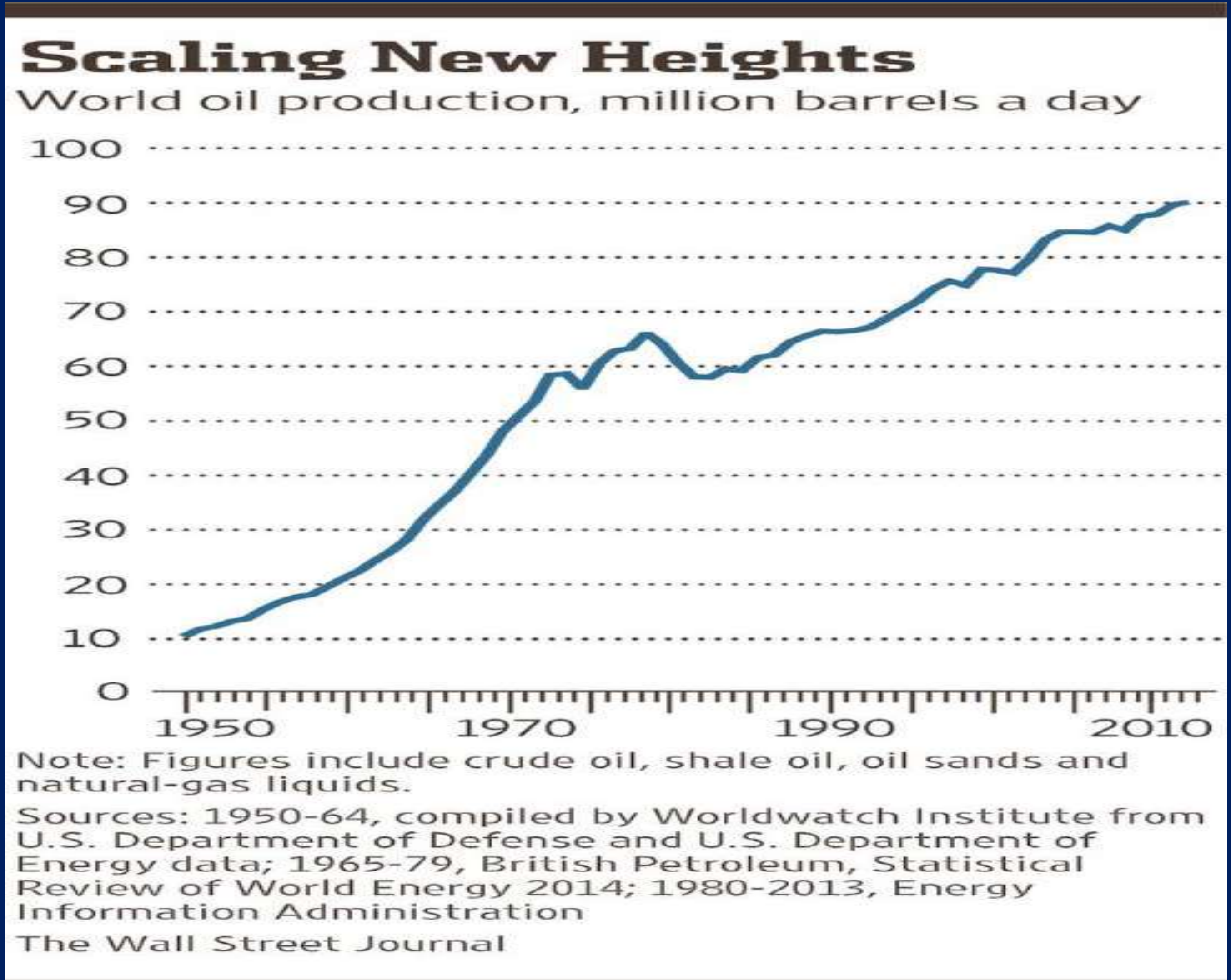
1984 ▲ | The first "steerable" drilling system is introduced, allowing for far more precision than older directional drilling.

1998 | BP drills a horizontal well that extends more than six miles in southern England. In 2011, Exxon will beat the record with a 7.7 mile "extended reach" well off Sakhalin Island, Russia.

Sources: Society of Petroleum Engineers; "The Boom" (1946 item); Photos from left: Getty Images, Corbis, Statoil, Schlumberger

http://www.wsj.com/articles/why-peak-oil-predictions-haven-t-come-true-1411937788

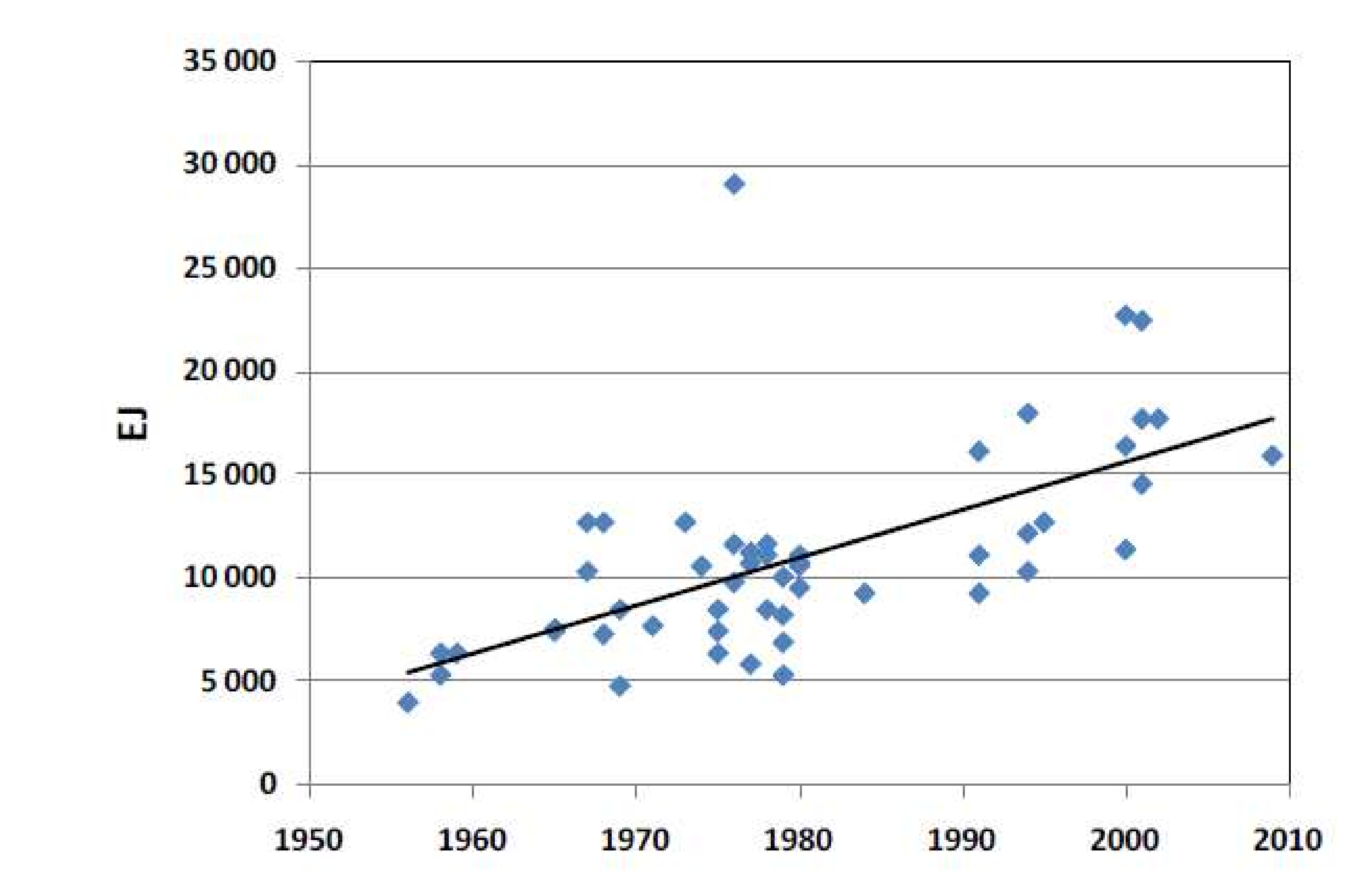
Oil Production



GEA – Reserve estimate

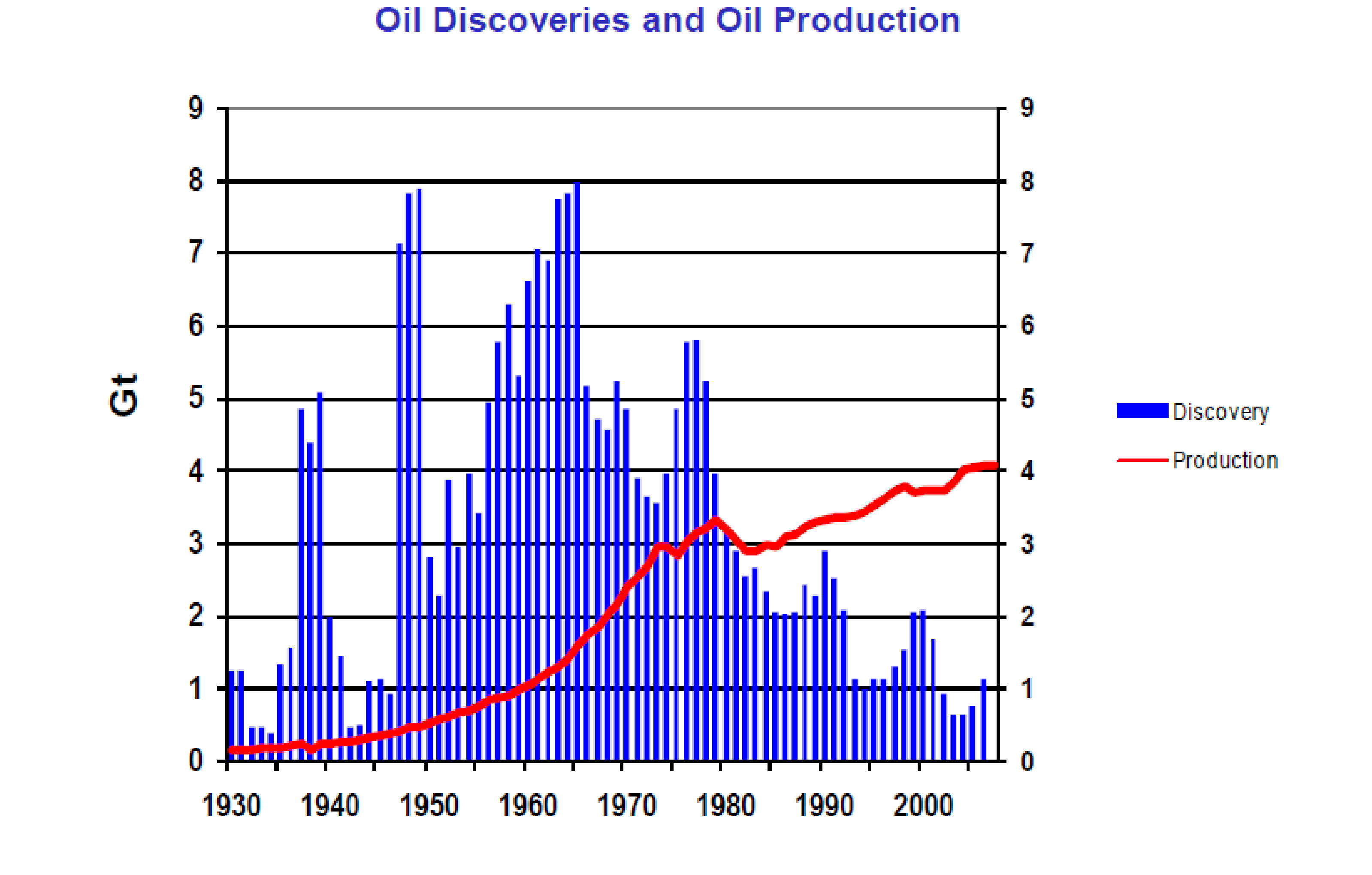
	Historical production through 2005	Production 2005	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	> 40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
Unconventional gas	113	9.6	20,100–67,100	40,200–121,900	> 1,000,000
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	> 2,600,000

World Oil Resources



Source: GEA Chapter 7

Oil Discoveries and Production



Source: GEA Chapter 7

Table 7.6 | Conventional oil reserves and resources.[a]

Region	Oil production 2009	Historical production till 2009	Reserves BP	Reserves BGR	Reserves USGS	Resources BGR	Resources USGS	Reserves + Resources BGR	Reserves + Resources USGS
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
USA	15.00	1246	162	162	183	420	476	582	659
CAN	6.70	200	189	28	36	101	21	129	57
WEU	8.98	329	74	88	179	186	492	275	671
EEU	0.28	47	4	6	15	13	11	19	26
FSU	27.64	1017	704	735	953	1008	952	1743	1906
NAF	10.38	336	389	388	252	184	158	573	410
EAF	0.00	0	0	4	0	13	7	17	7
WCA	6.07	214	263	254	142	302	375	556	517
SAF	3.78	48	77	77	24	150	97	227	121
MEE	50.78	1823	4308	4286	2967	889	1654	5175	4621
CHN	7.90	220	85	84	142	97	95	181	237
OEA	1.02	11	26	26	0	32	1	58	1
IND	1.57	46	33	33	40	17	18	50	58
OSA	0.14	4	4	2	3	13	11	15	13
JPN	0.01	2	0	0	0	0	0	1	0
OCN	1.20	41	25	24	94	44	108	69	202
PAS	4.90	203	68	65	22	88	63	153	86
LAC	20.30	862	1203	479	426	614	853	1093	1279
Circum-Arctic							768		768
Total	166.68	6647	7615	6742	5477	4172	6161	10914	11,638

Oil Reserve Supply Curves

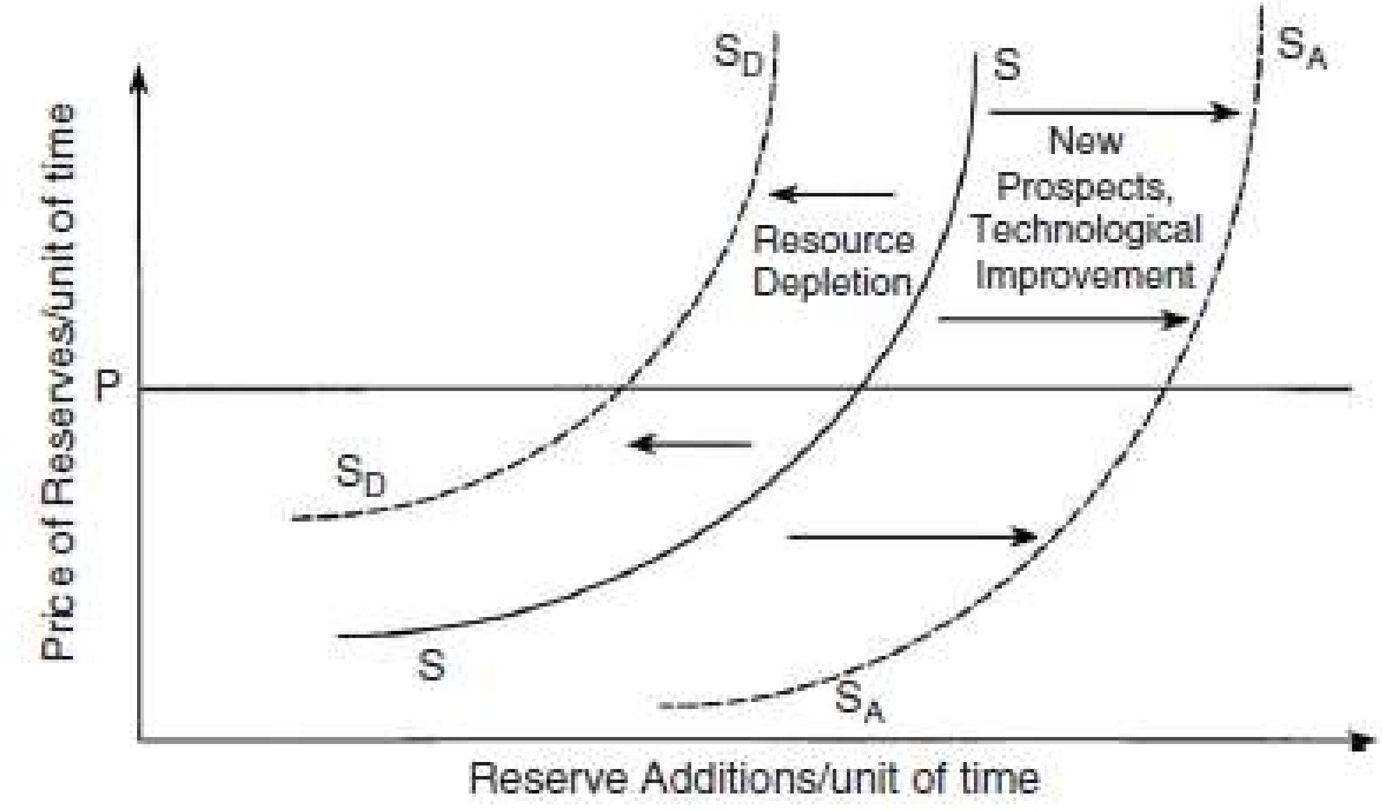
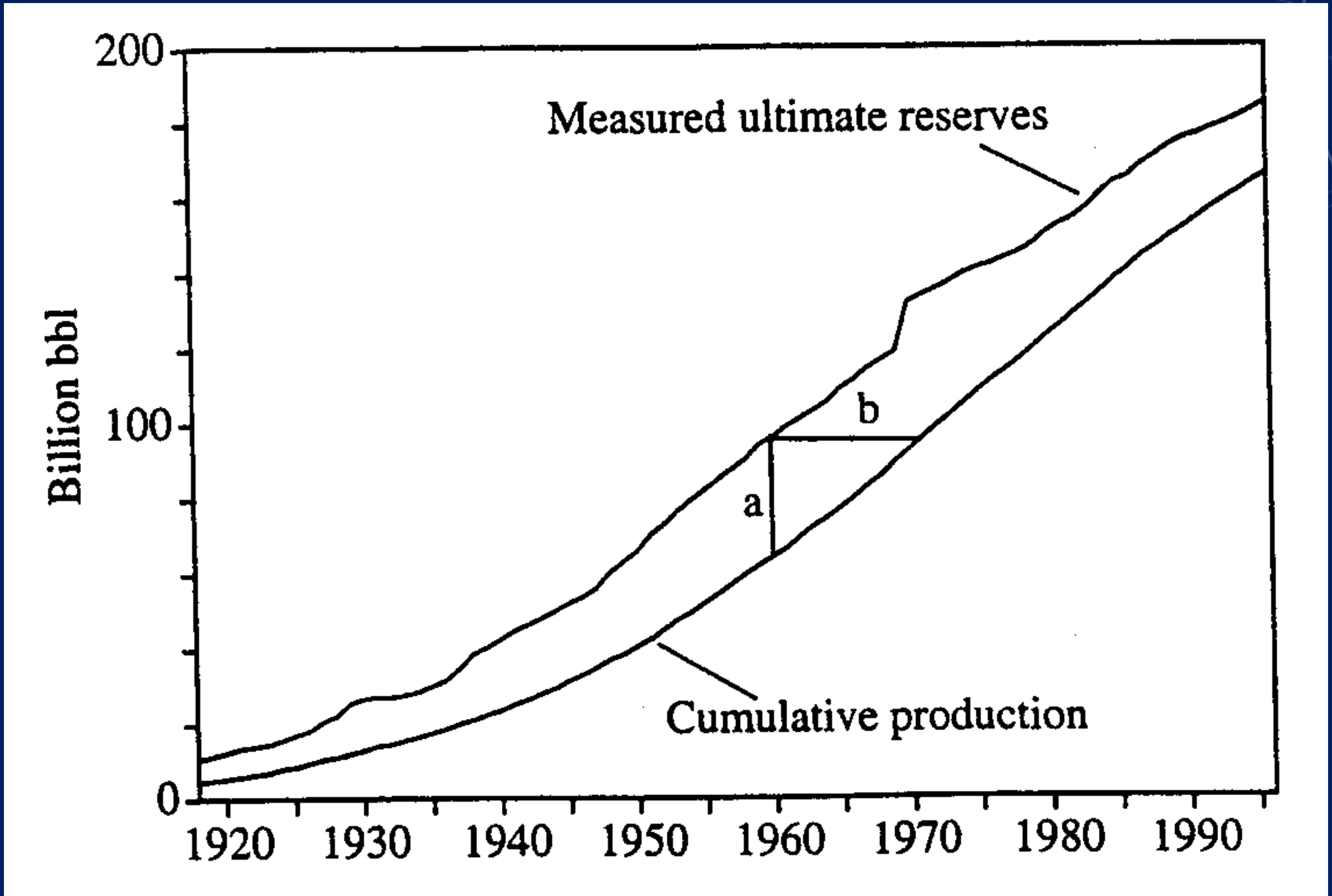


Fig. 3. Oil reserve supply curves.

Source: Watkins, 2006

Reserves and Production – Oil US

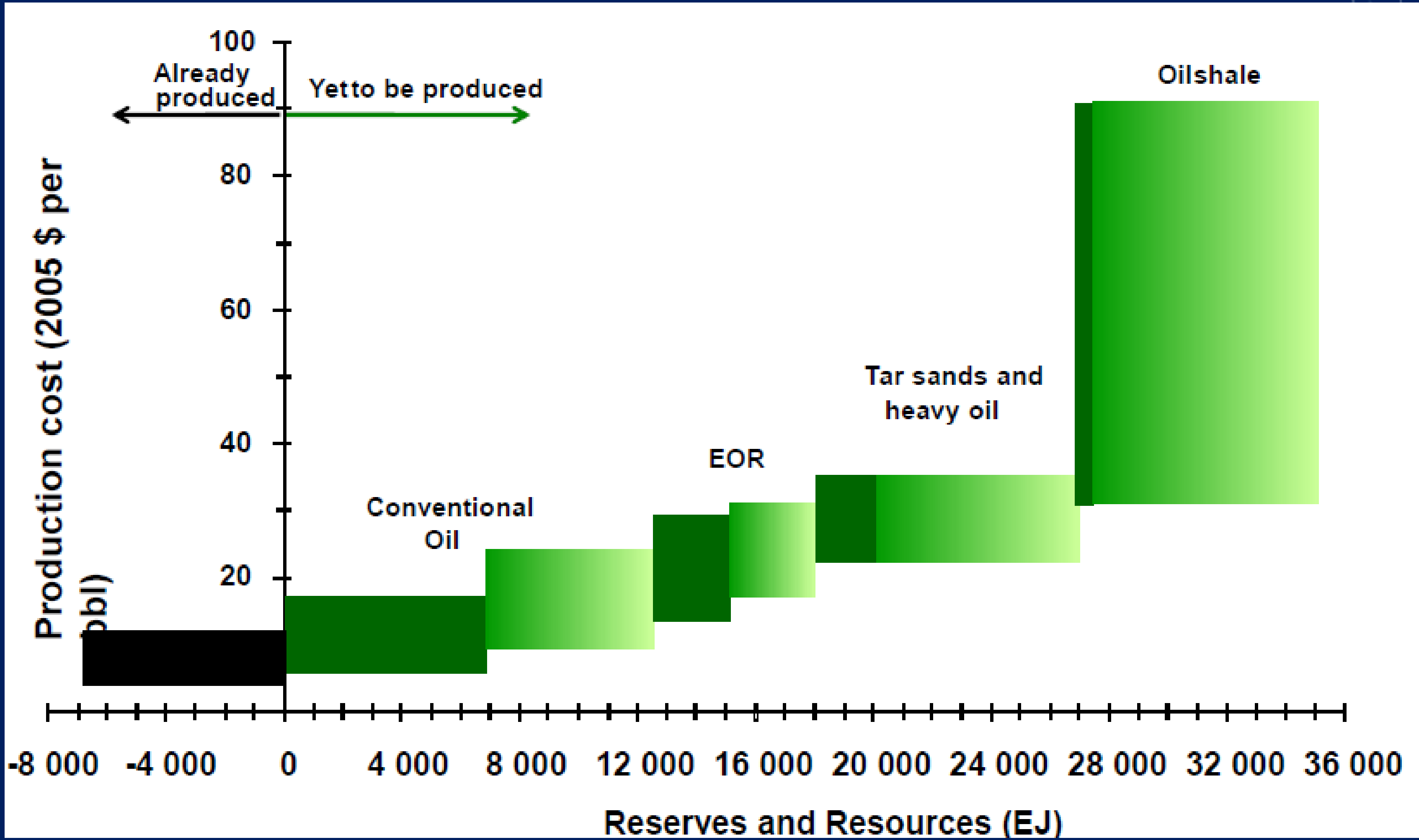


Mc Cabe, 1998

	Term	Definition	Physical properties
Oil type	Conventional oil	Oil that is mobile in situ and can be produced economically using conventional methods	μ < 100 mPa·s[a] Low S content
	Viscous oil	Inclusive term for the next three categories below	μ > 100 mPa·s
	Heavy oil	Oil that is only slightly mobile in situ, usually requiring stimulation techniques to improve mobility	μ 100–10,000 mPa·s S content <1%
	Extra-heavy oil	Oil of exceptionally high gravity (ρ >1.0) that has some mobility because of high in situ temperatures (particularly used to refer to Orinoco, Venezuela oils)	μ <10,000 mPa·s, ρ >1.0 S content >1%
	Bitumen	Oil that is immobile in situ so that large viscosity reductions or mining methods are needed	μ >10,000 mPa·s ρ >1.0[b] S content >1%
Rock strata	Oil sands	Sand strata > 25% porosity, containing extra-heavy oil or bitumen, more viscous than heavy oil	k >0.5 Darcy, usually μ > 1000 mPa·s
	Heavy-oil NFCRs	Naturally fractured carbonate reservoirs (NFCRs) containing viscous oil	μ >100 mPa·s Porosity 10–20%
	Oil shale	Kerogenous shales and marls that produce more than 50 l/t of product during Fischer Assay tests	Porosity >15–20%

Source: GEA Chapter 7

Liquid fuel Supply curve



Source: GEA Chapter 7

Fossil and Uranium reserves

	Historical production through 2005	Production 2005	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	> 40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
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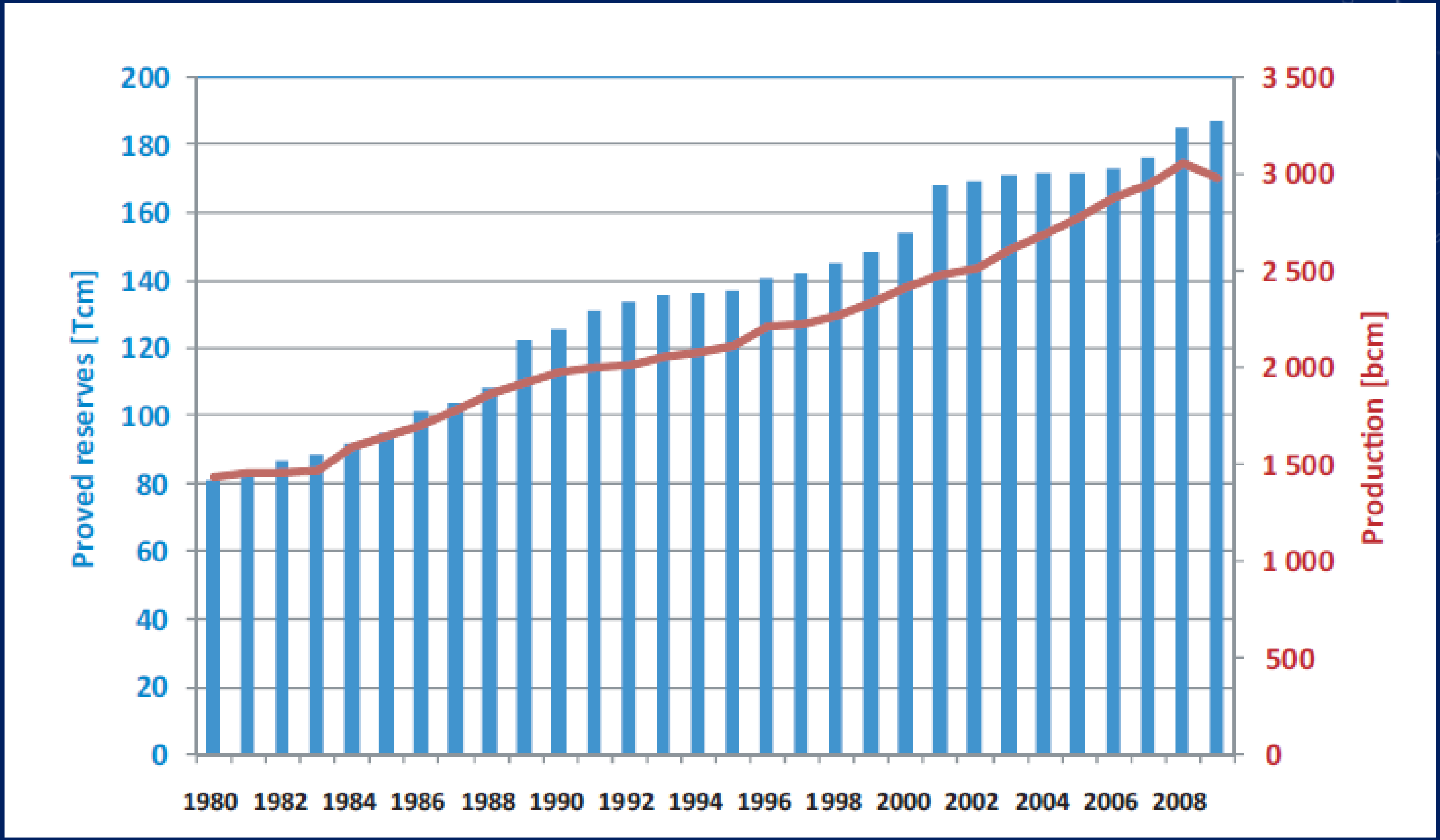
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	> 2,600,000

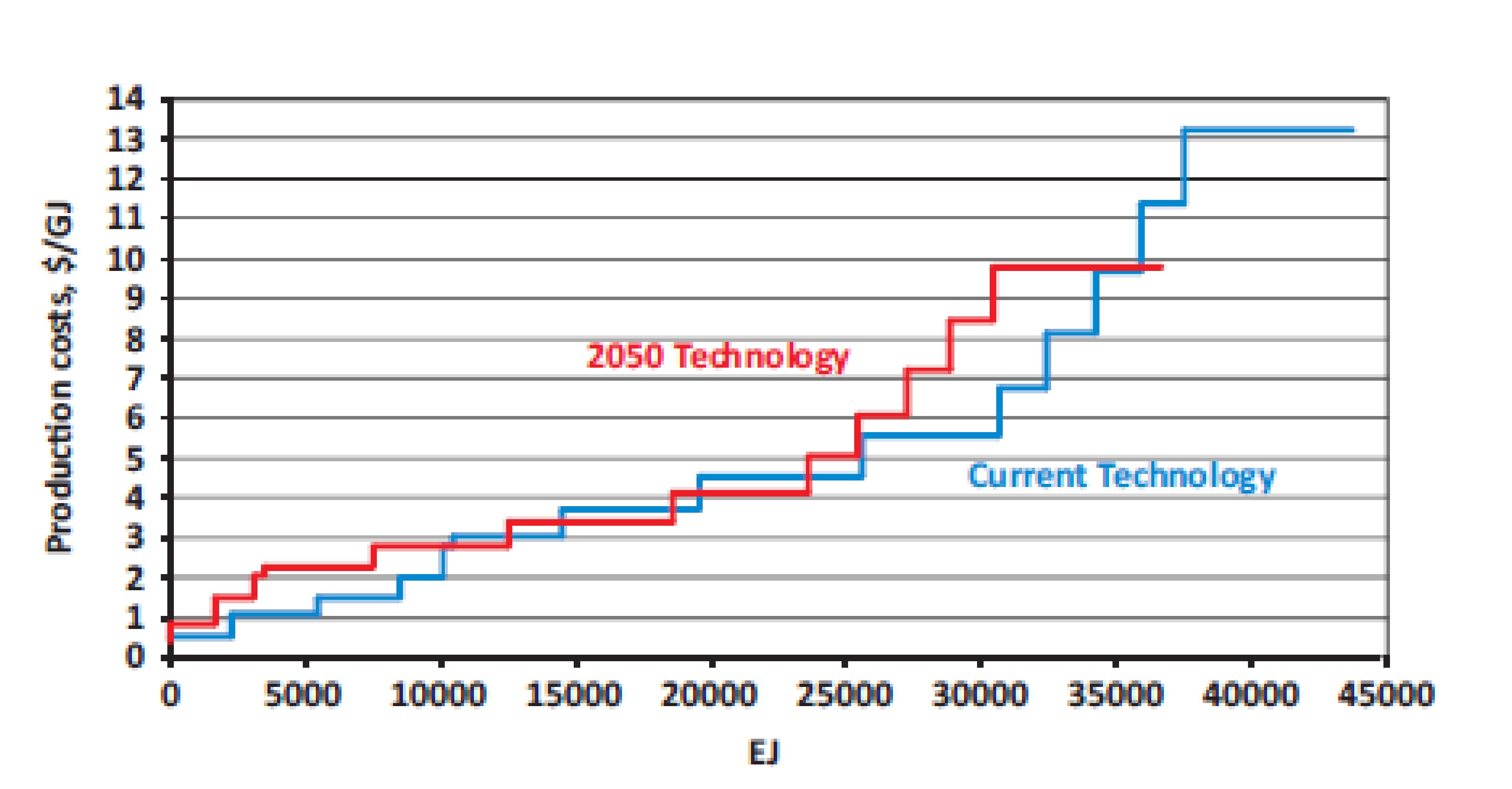
Source: GEA Chapter 7

Natural Gas Reserves/ Production



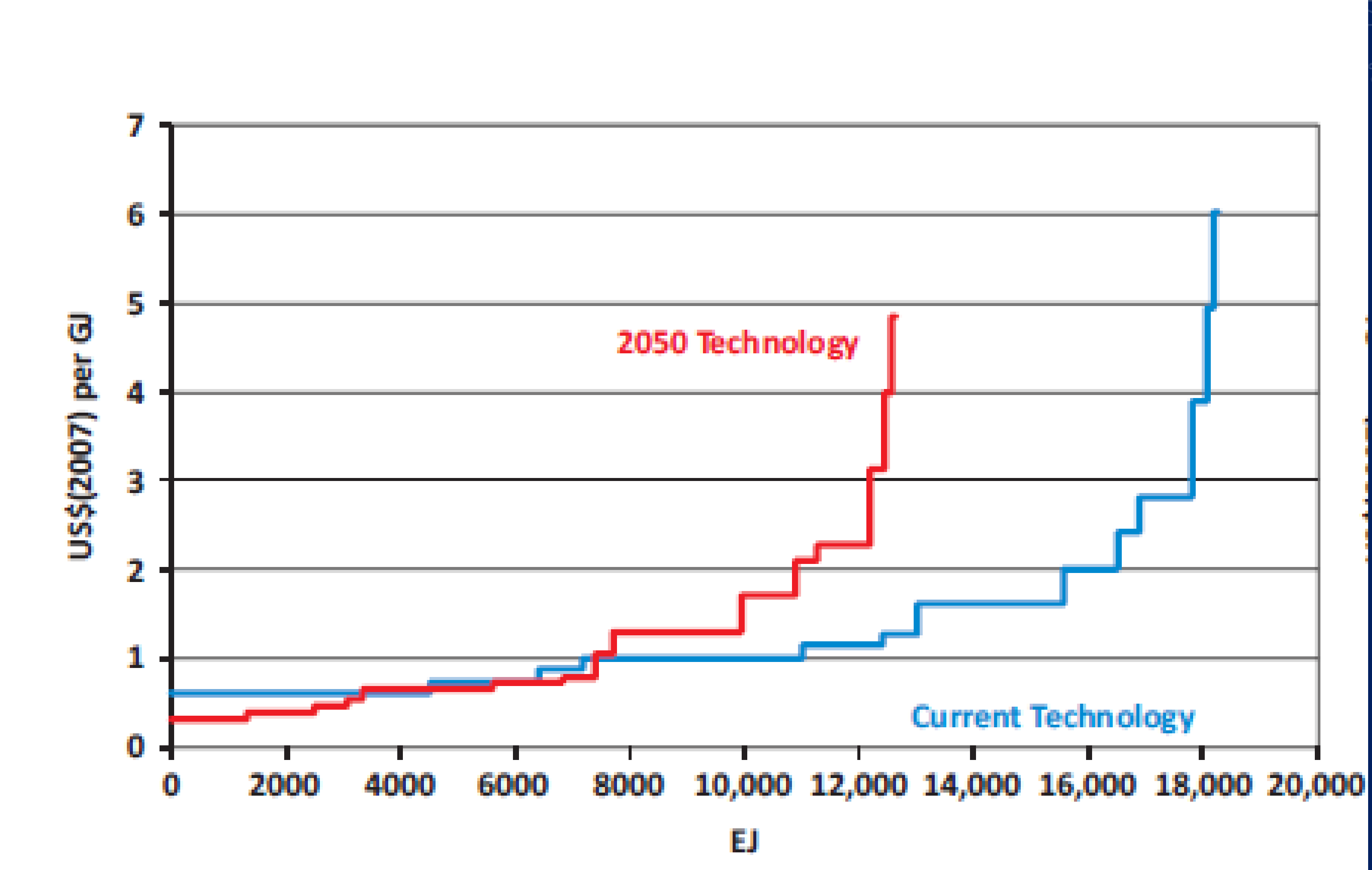
Source: GEA Chapter 7

Gas Supply curve



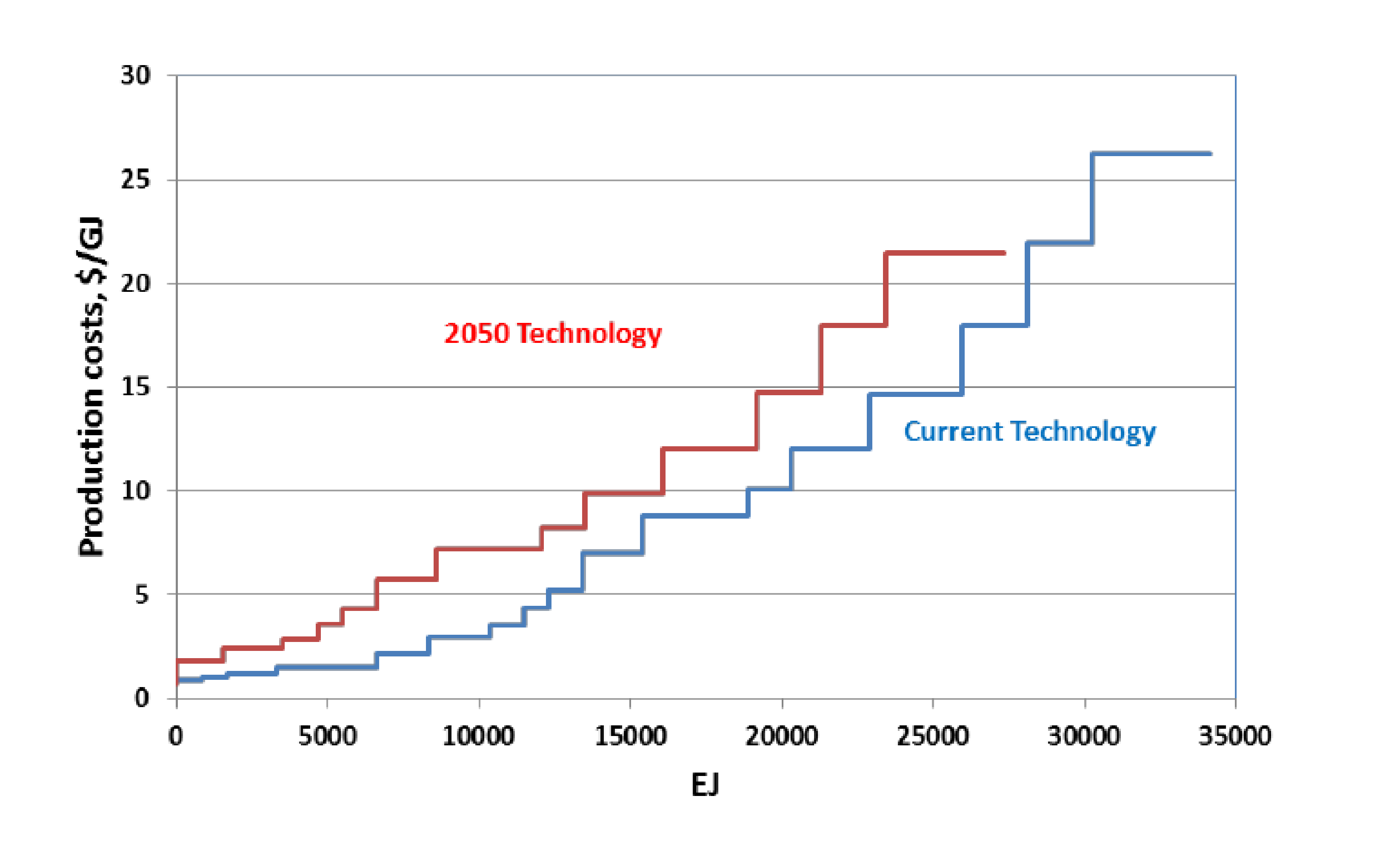
Source: GEA Chapter 7

Supply Curves for Coal



Source: GEA Chapter 7

Oil Supply Curve



Source: GEA Chapter 7

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