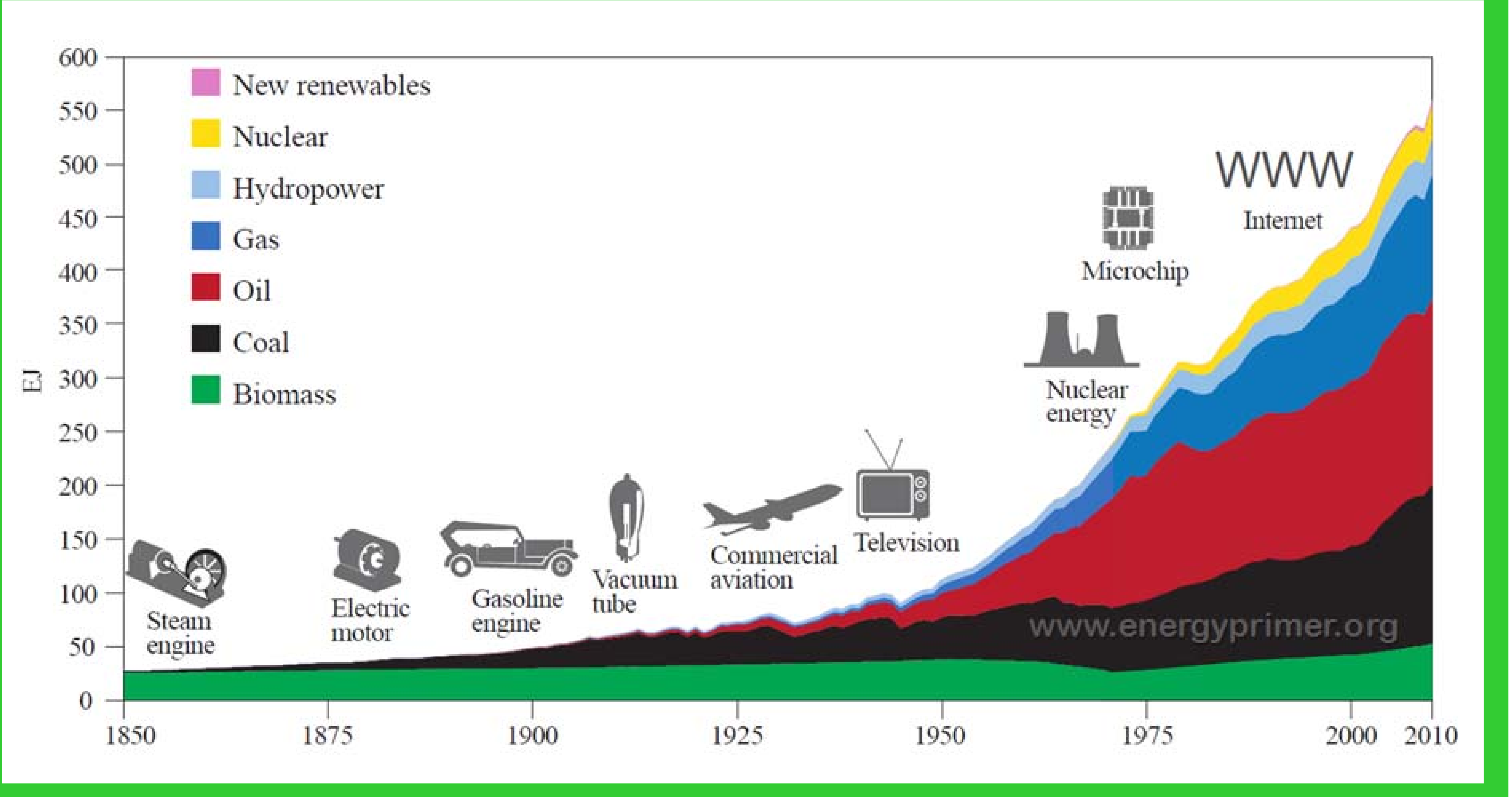
6

Fallstudie II

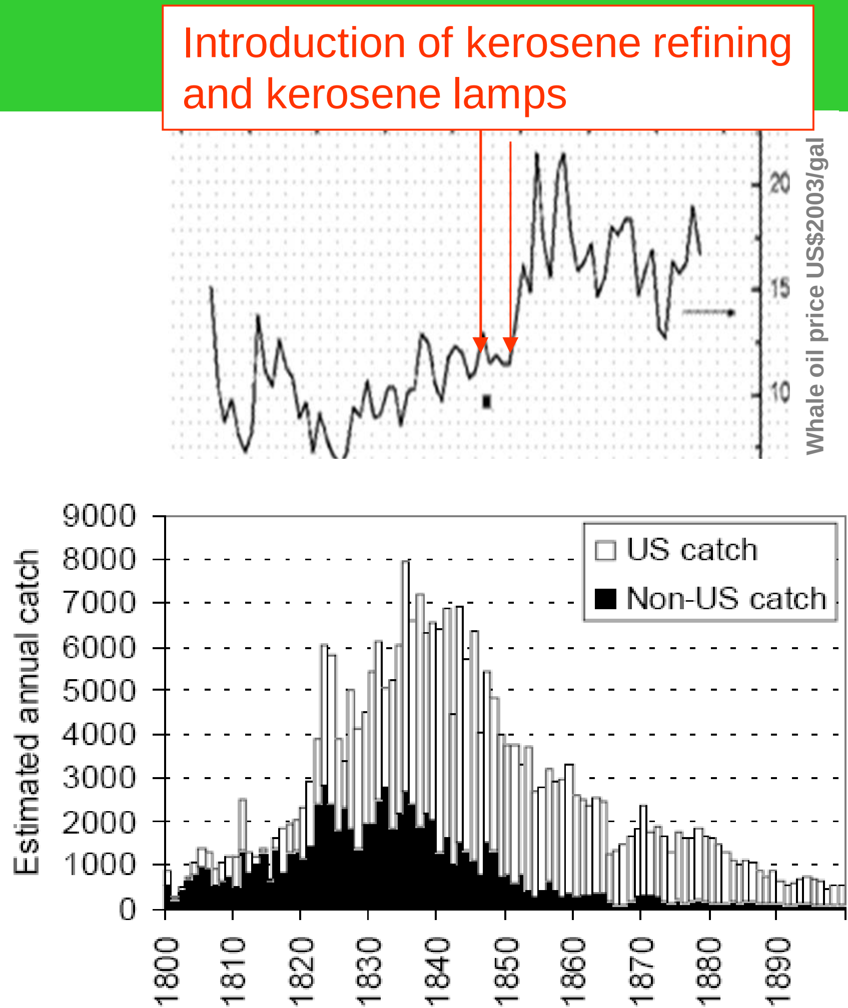
Mineralische und energetische Rohstoffe

Arnulf Grübler

World Energy Supply (EJ)

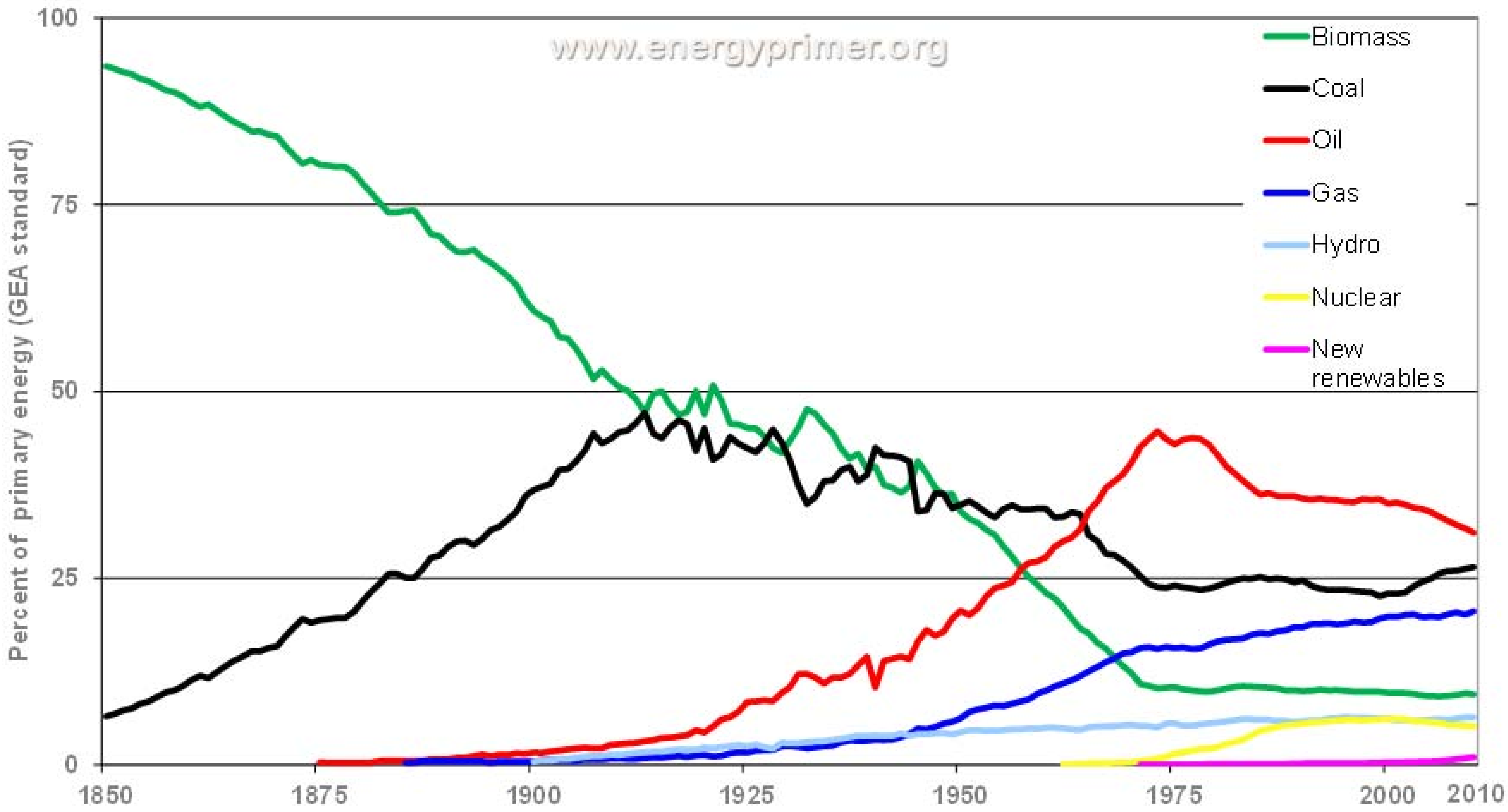


Whale Catch and Whale Oil Prices



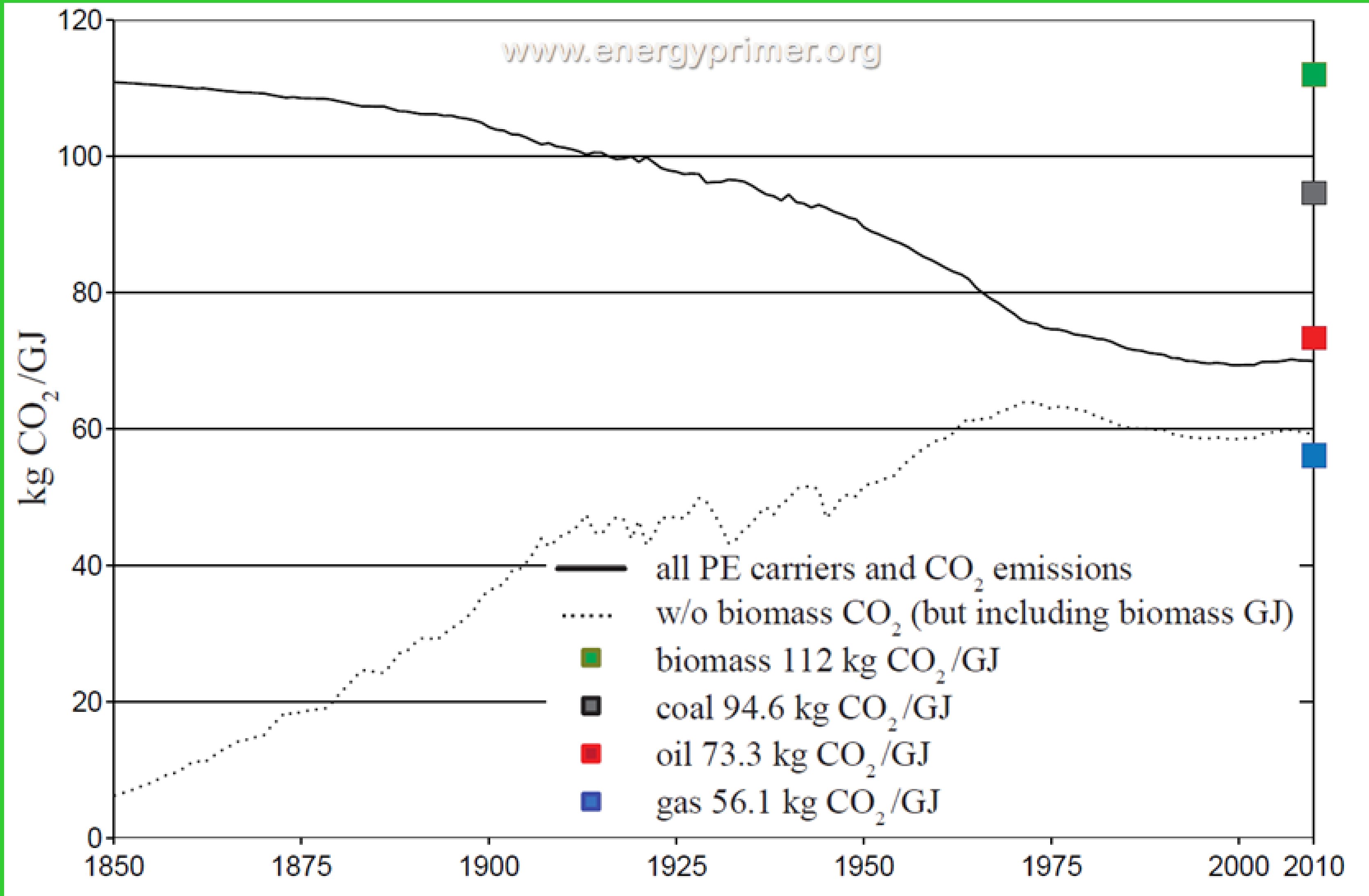
Source: Sperm catch: P. Best, 2002, IWC SC/56/IA5; Prices: U. Bardi, 2004, based on Starbuck, 1878.

Primary Energy Substitution

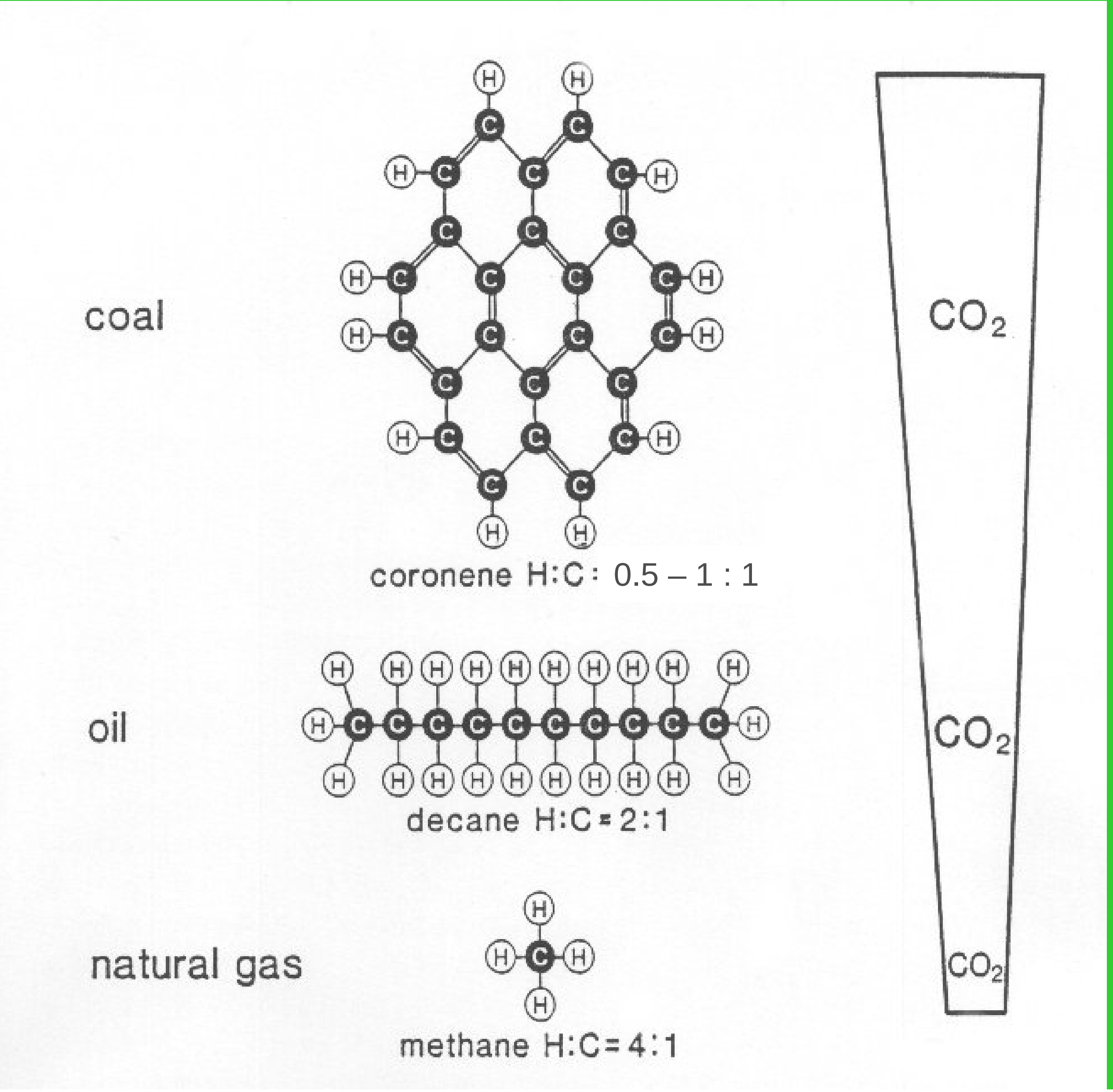


Technik & Umwelt **Arnulf Grübler**

World - Carbon Intensity of Primary Energy

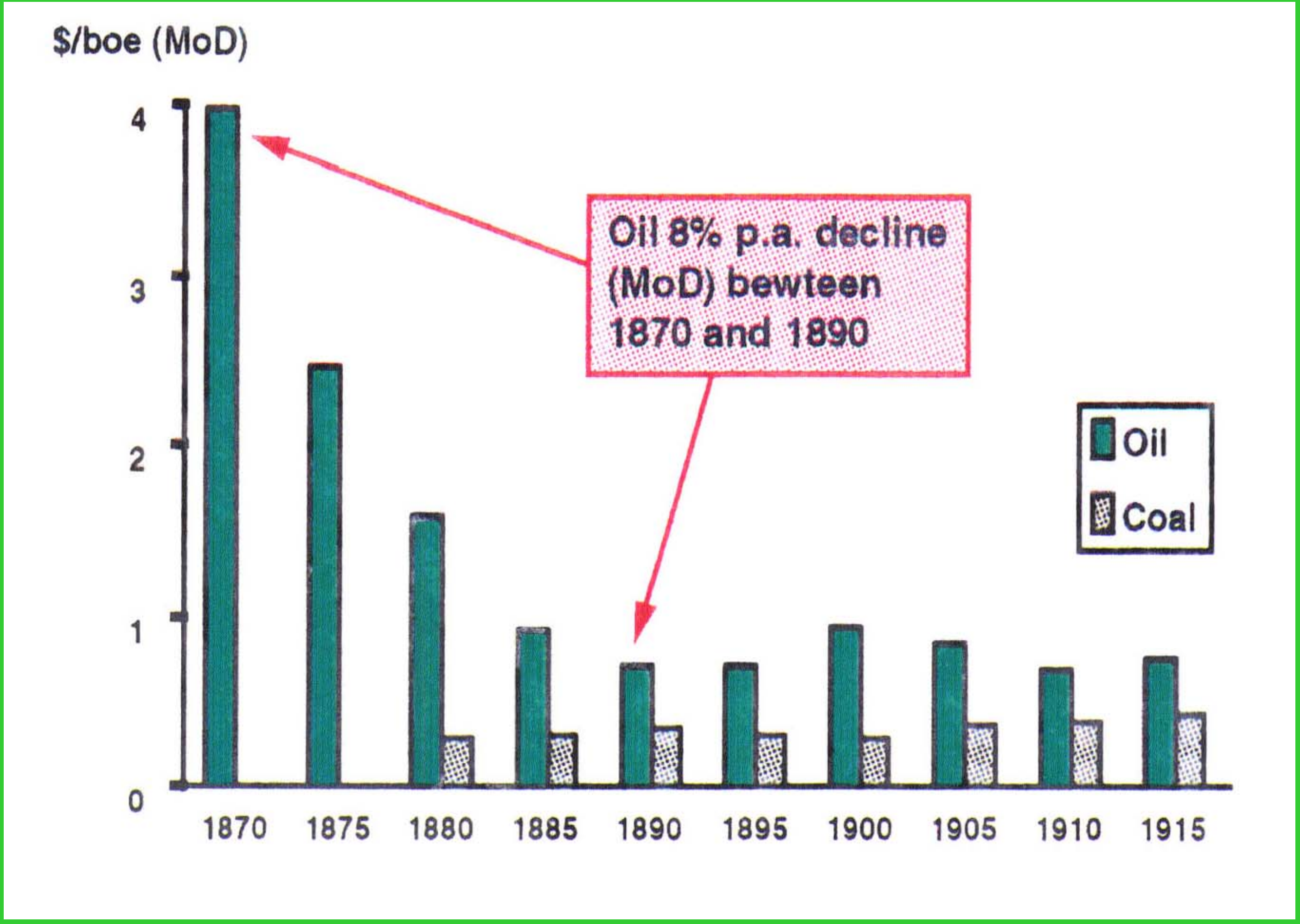


H:C Ratios (Ruhrgas, 1996)

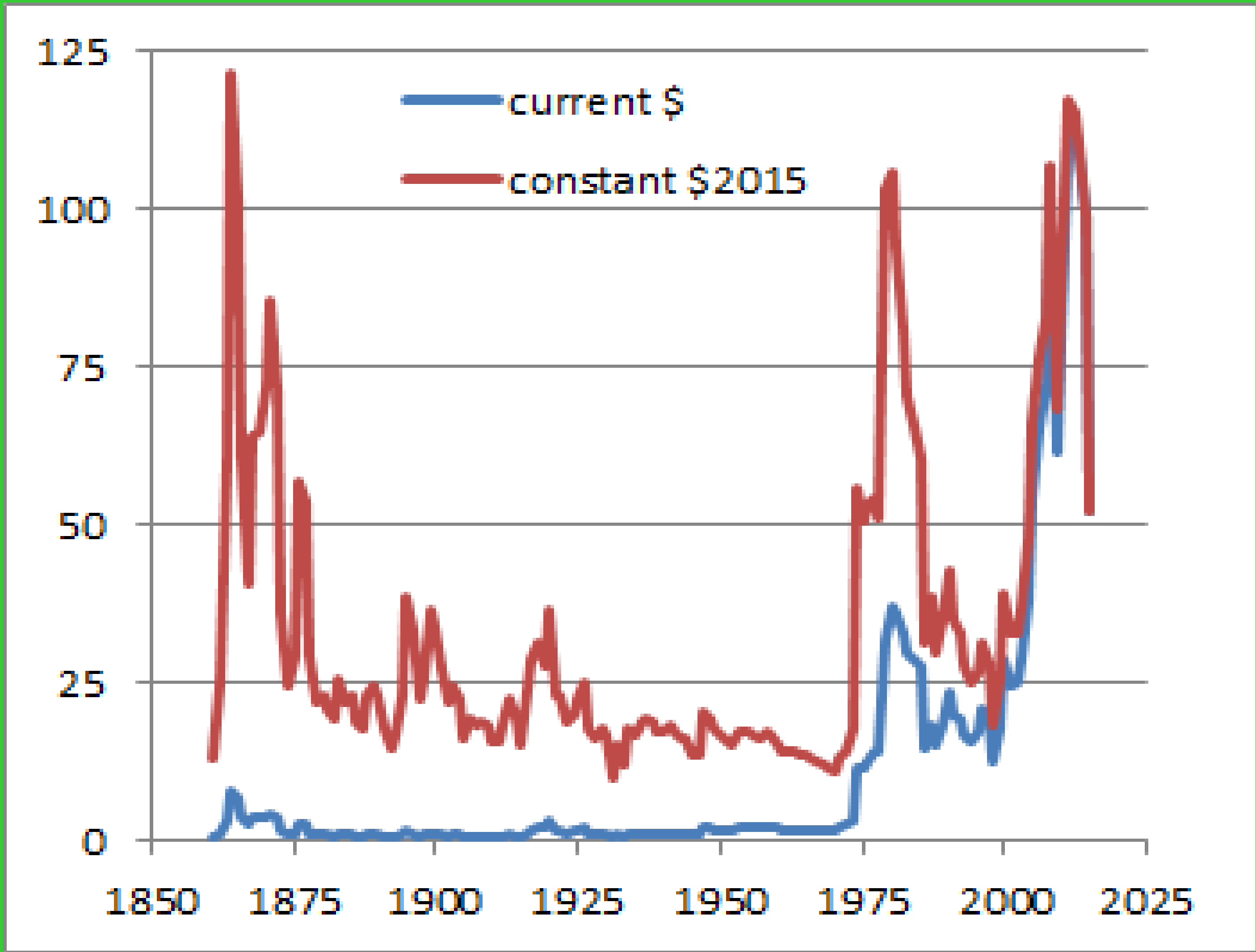


Price of Oil and Coal 1870-1915

Source: Group Planning SHELL, 1994.

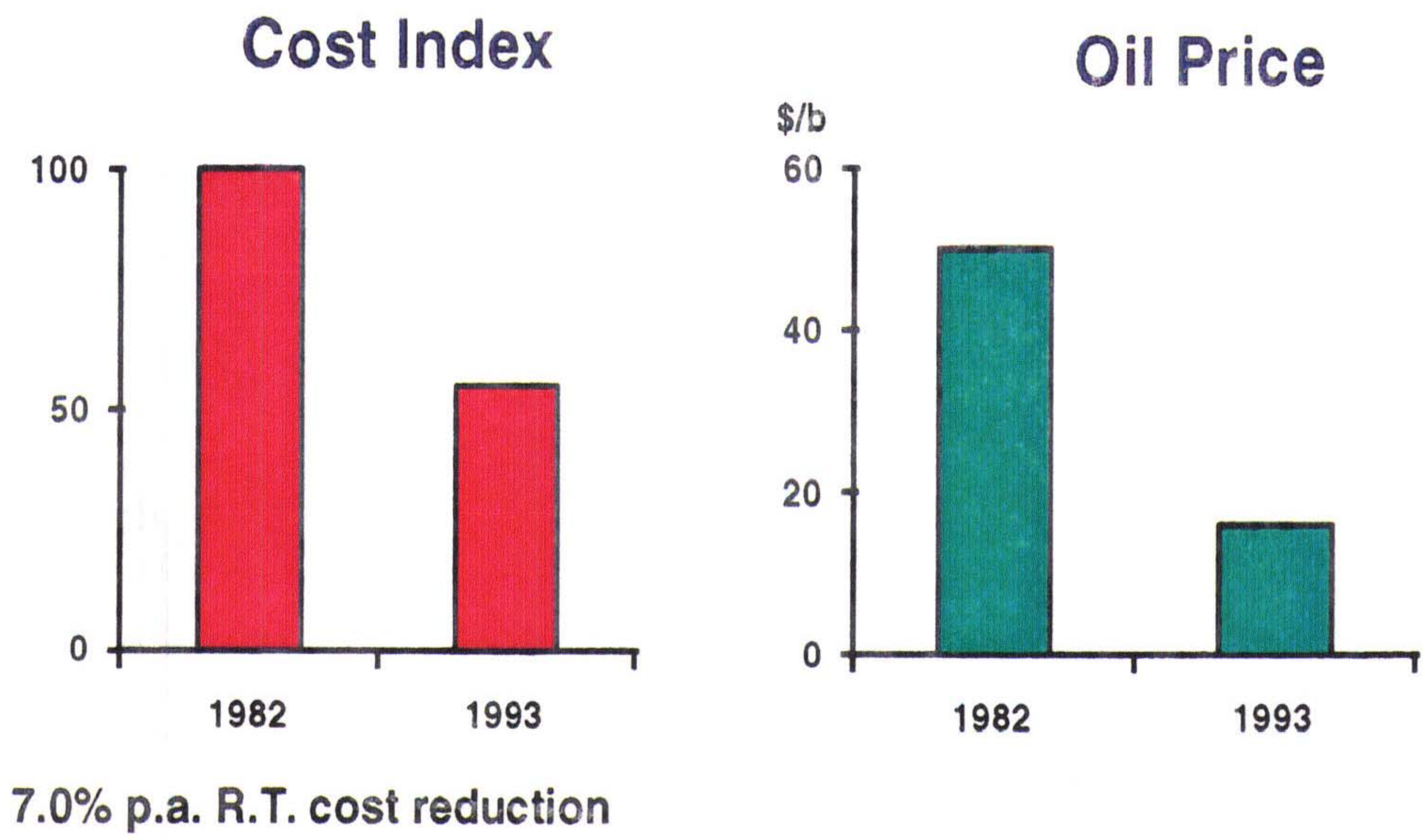


Crude Oil Prices (BP, 2016)



Capacity Cost of Troll Field (North Sea)

Source: Group Planning SHELL, 1994.



High prices beget high costs; low prices beget low costs (M. Adelmann)

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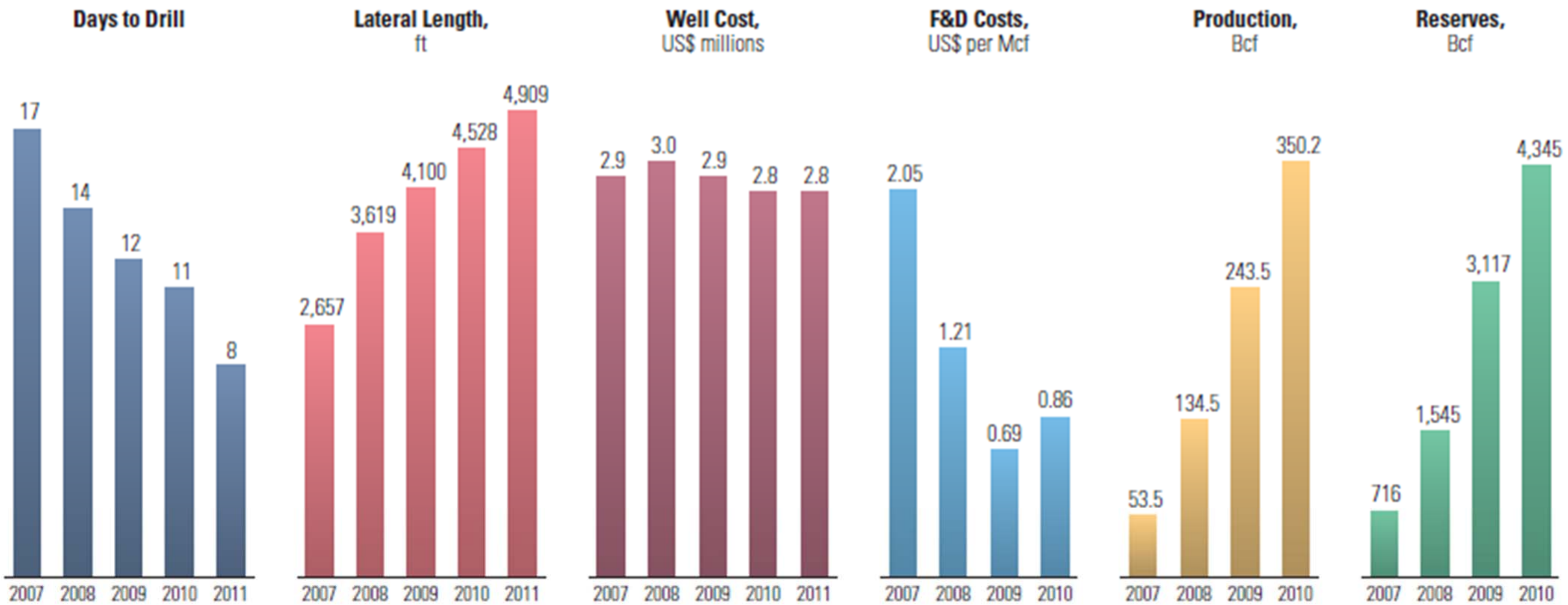
Fracking Productivity Increases (Southwestern Energy)



^ Continuous process improvement. Over a four-and-a-half year period, from 2007 to 2011, Southwestern Energy reduced days to drill (dark blue) by 52%, even though the lateral length was increased by more than 84% (pink). Well costs (dark red) were flat to slightly lower during the period but the company's finding and development costs (F&D, light blue) were significantly reduced during the period. Production (gold) and reserves (green) greatly increased during the study period. (Data for 2011 are for the first six months of the year.)

Source: Schlumberger, 2011

Recurring Perception of Scarcity

"…the data at hand in regard to the gas still available underground … make it probable that the annual output will never be very much more than it was during the period 1916 - 1920."

R.S. McBride and E.G. Sievers (USGS),

Mineral Resources of the United States, 1921, p.340.

US gas production:

22 Mtoe in 1920

100 Mtoe in 1995

A Digression - Hotelling's Rule (1931): Optimal Production of Non-renewable Resources

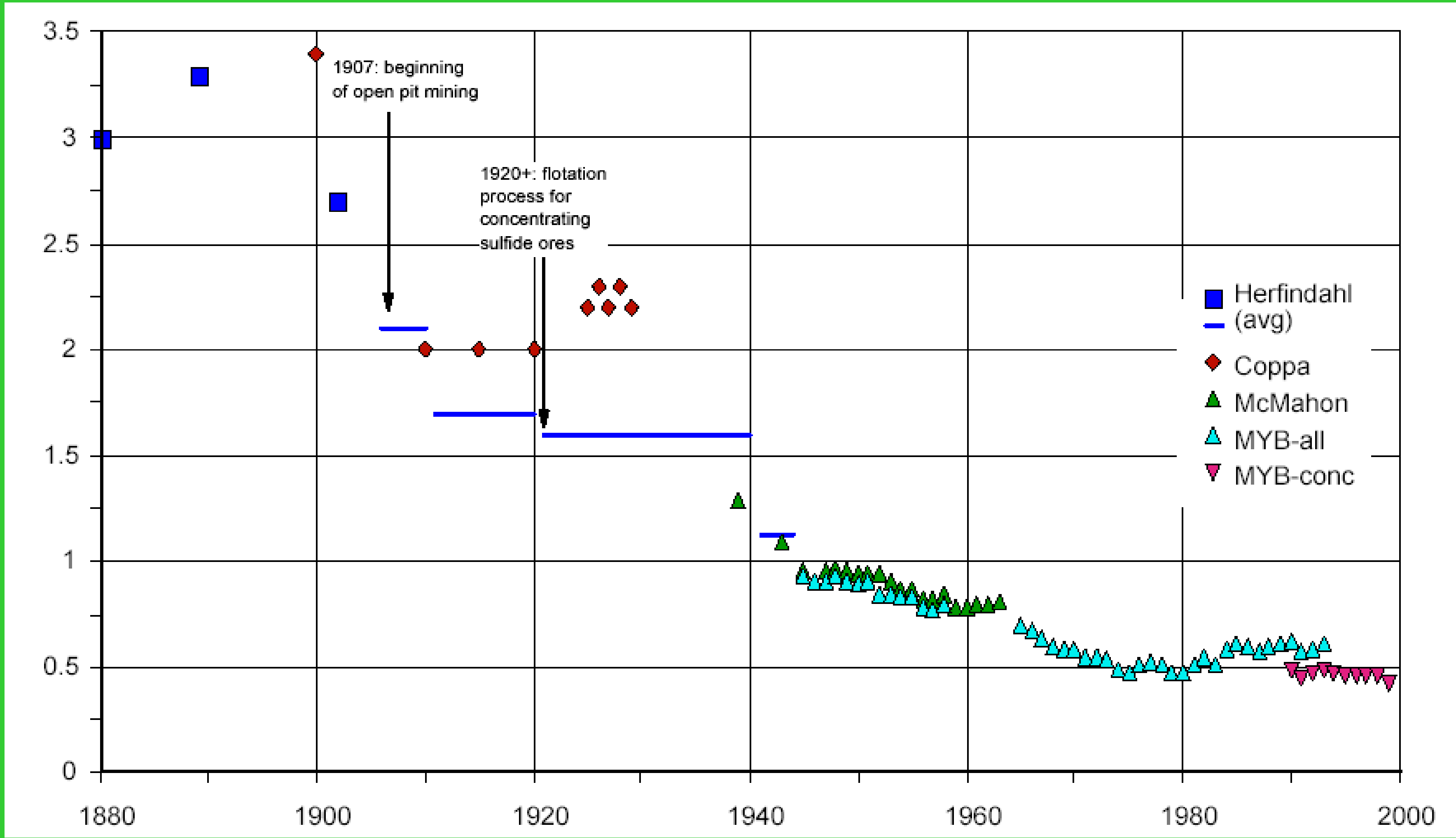
- Assuming: Static deposit, static technology, perfect (price) foresight
- Investment choice: Develop deposit or invest money in financial market

$$\Delta P_t / P_t = r_t$$

- Optimal production: resource prices rise at least with general interest rate
- History: Prices decline, costs decline even faster (productivity, technology, substitution)

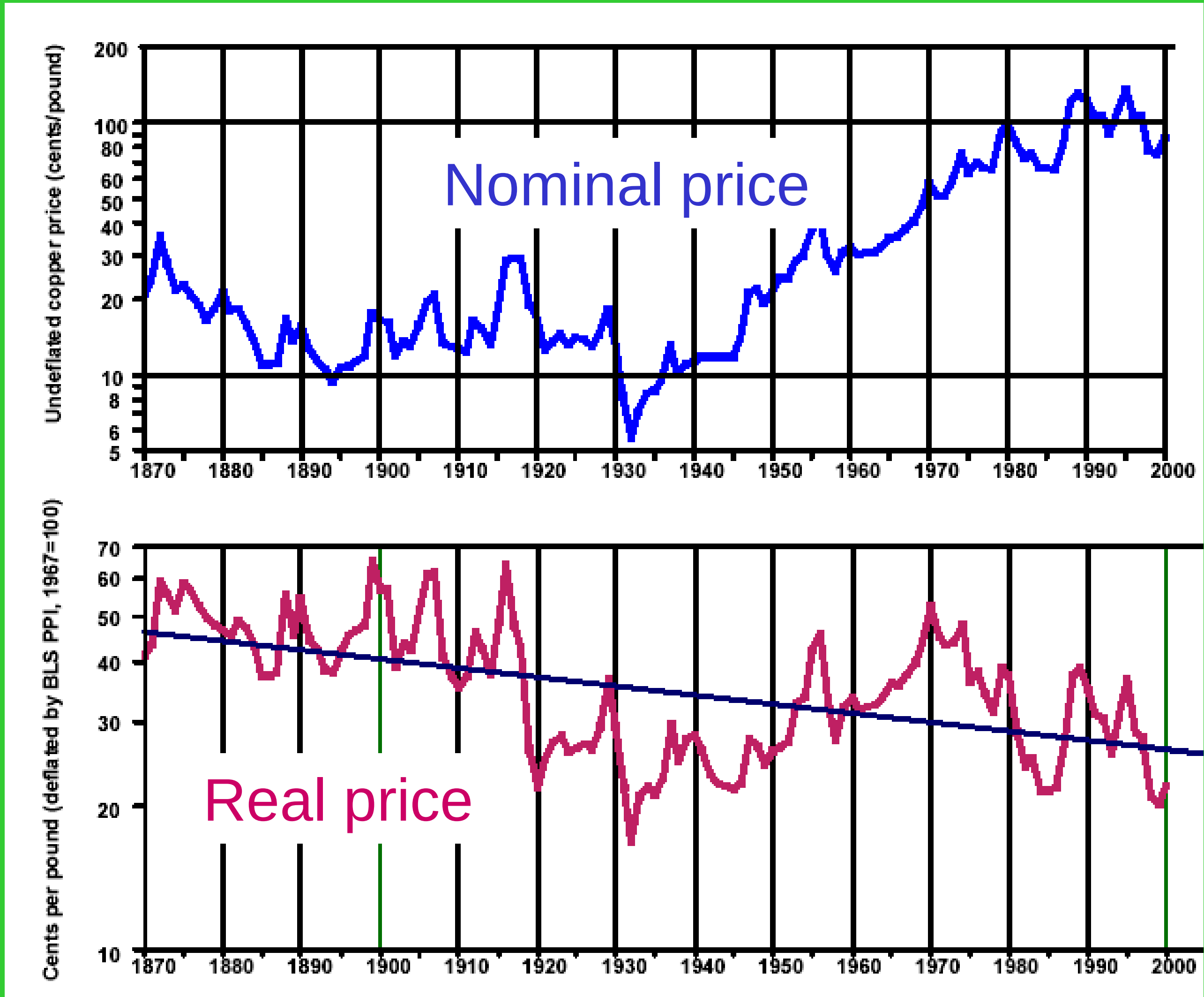
US – Copper Ore Grades (Percent)

Source: Ayres et al., 2001.



US Copper prices (cents/lb)

Source: Ayres et al., 2001.

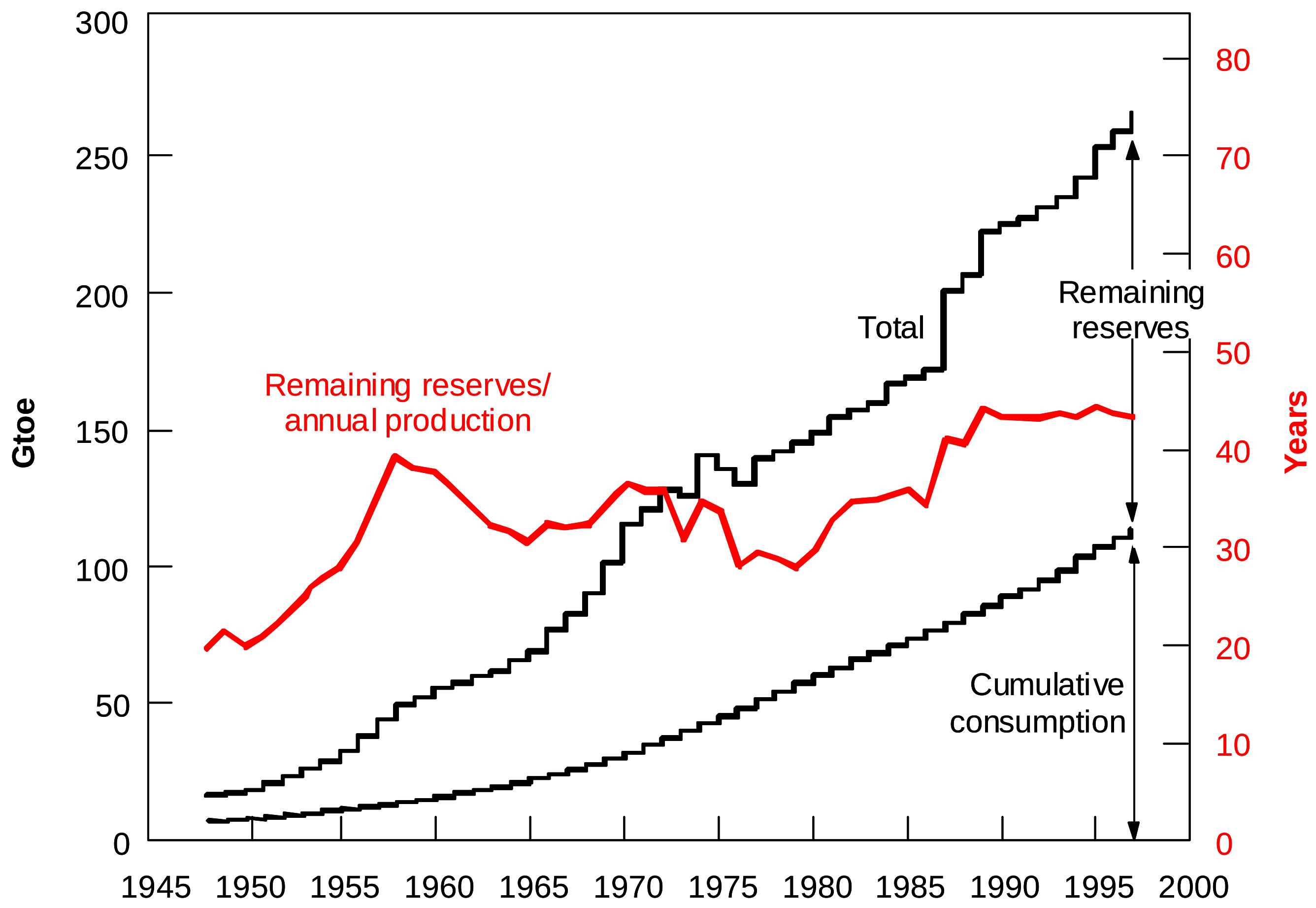


Changing Mineral Reserves

(Cohen, 1995)

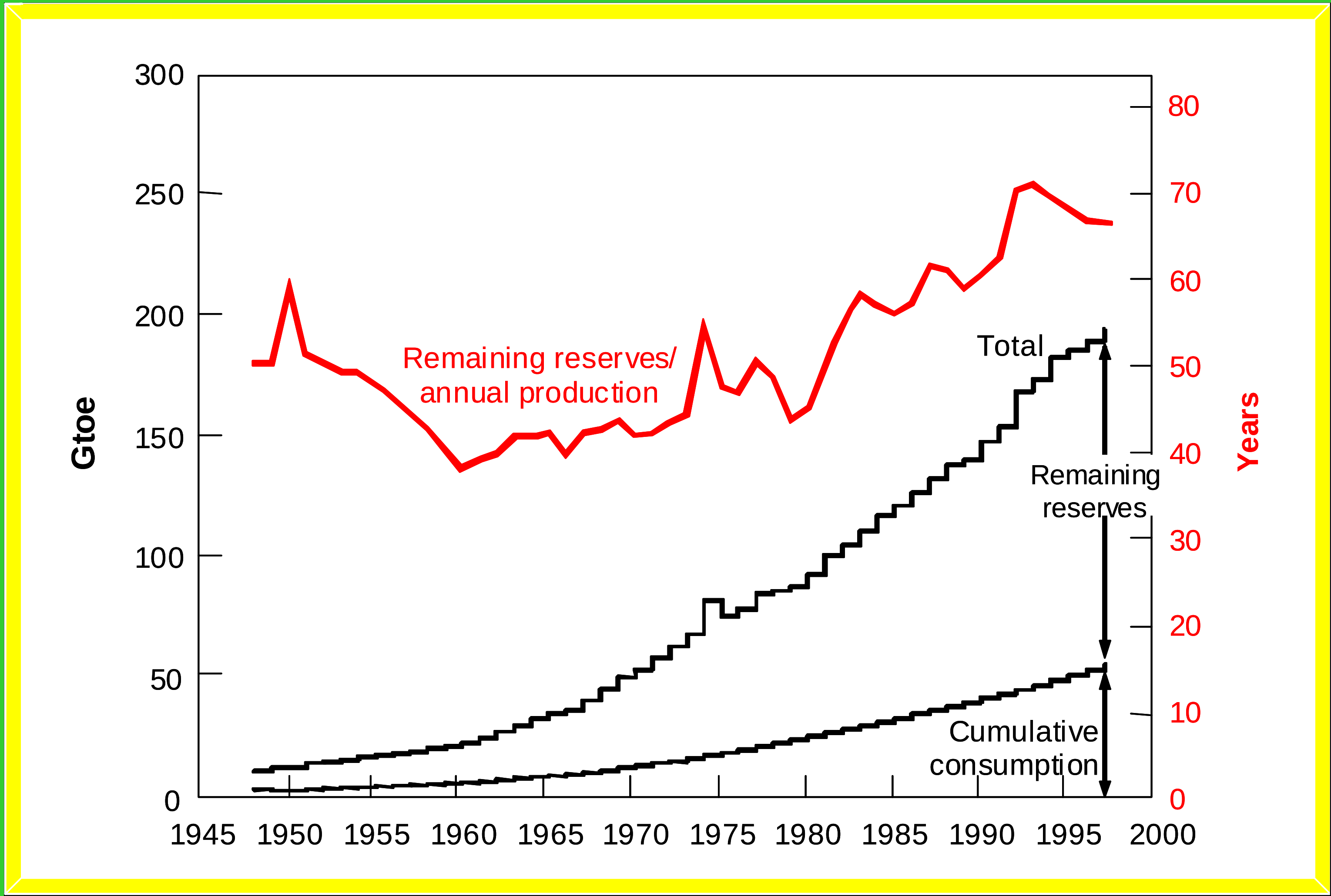
Mineral	Reserves 1950	Production 1950-1980	Reserves 1980
Copper	100	156	494
Iron	19,000	11,040	93,466
Aluminum	1,400	1,346	5,200
Lead	40	85	127

Recoverable Conventional Oil Reserves and Cumulative Production



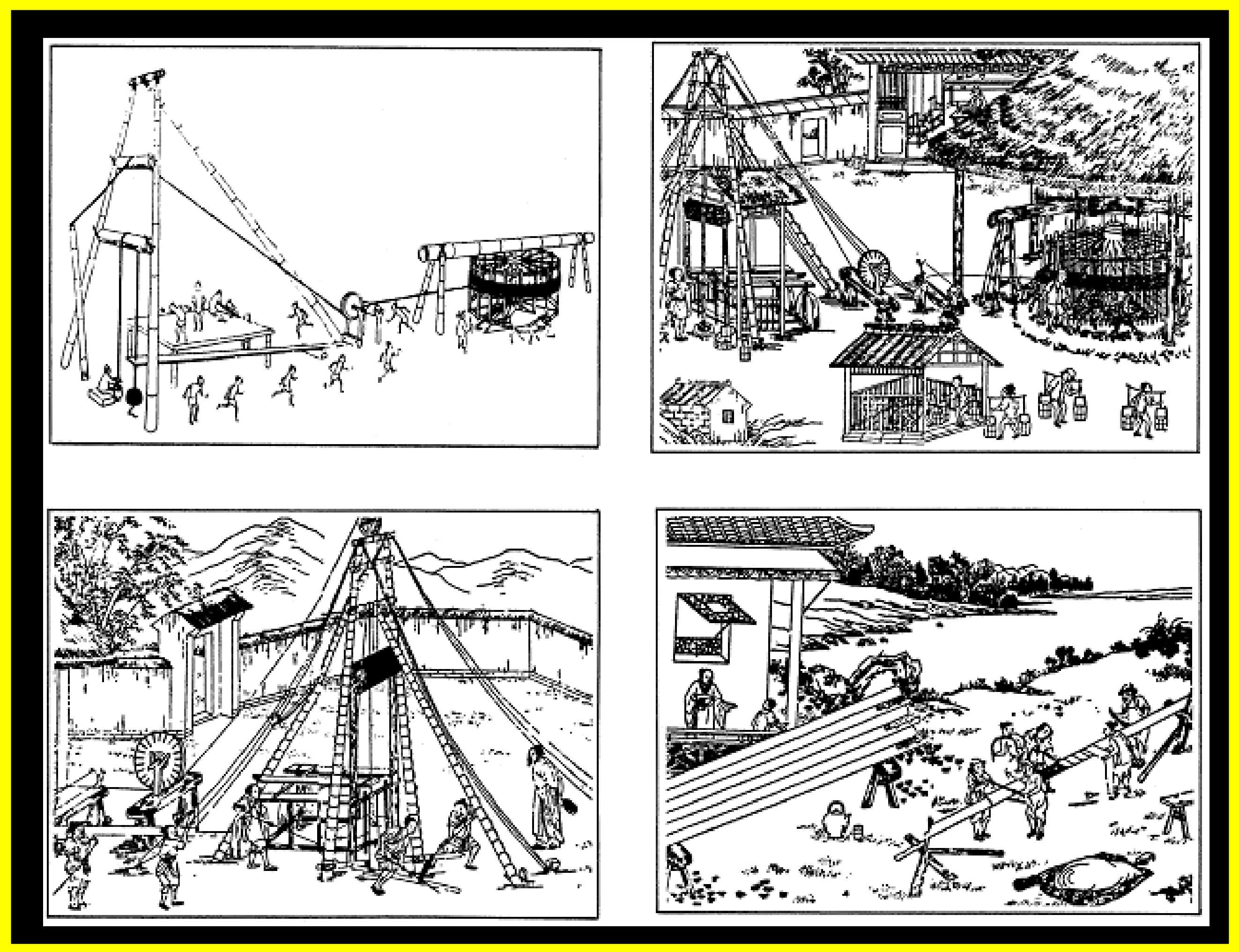
Nakicenovic *et al.*, 1998; BGR, 1998.

Recoverable Conventional Gas Reserves and Cumulative Production



Nakicenovic *et al.*, 1998; BGR, 1998.

Natural Gas Use in China



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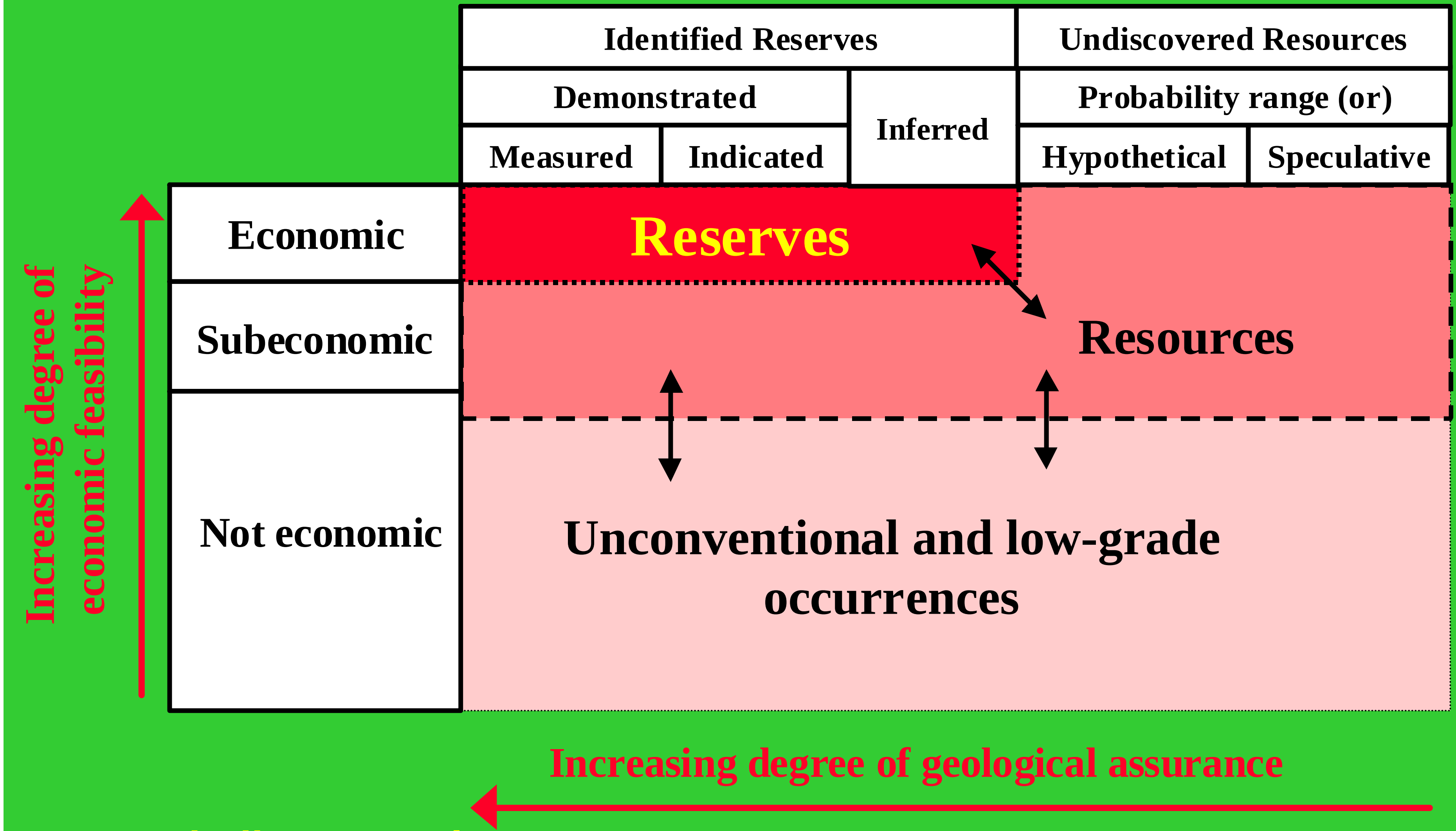
Also sprach…

Zarathustra……

Resource Classification: The McKelvey Box
(modified after Fettweis, 1978)



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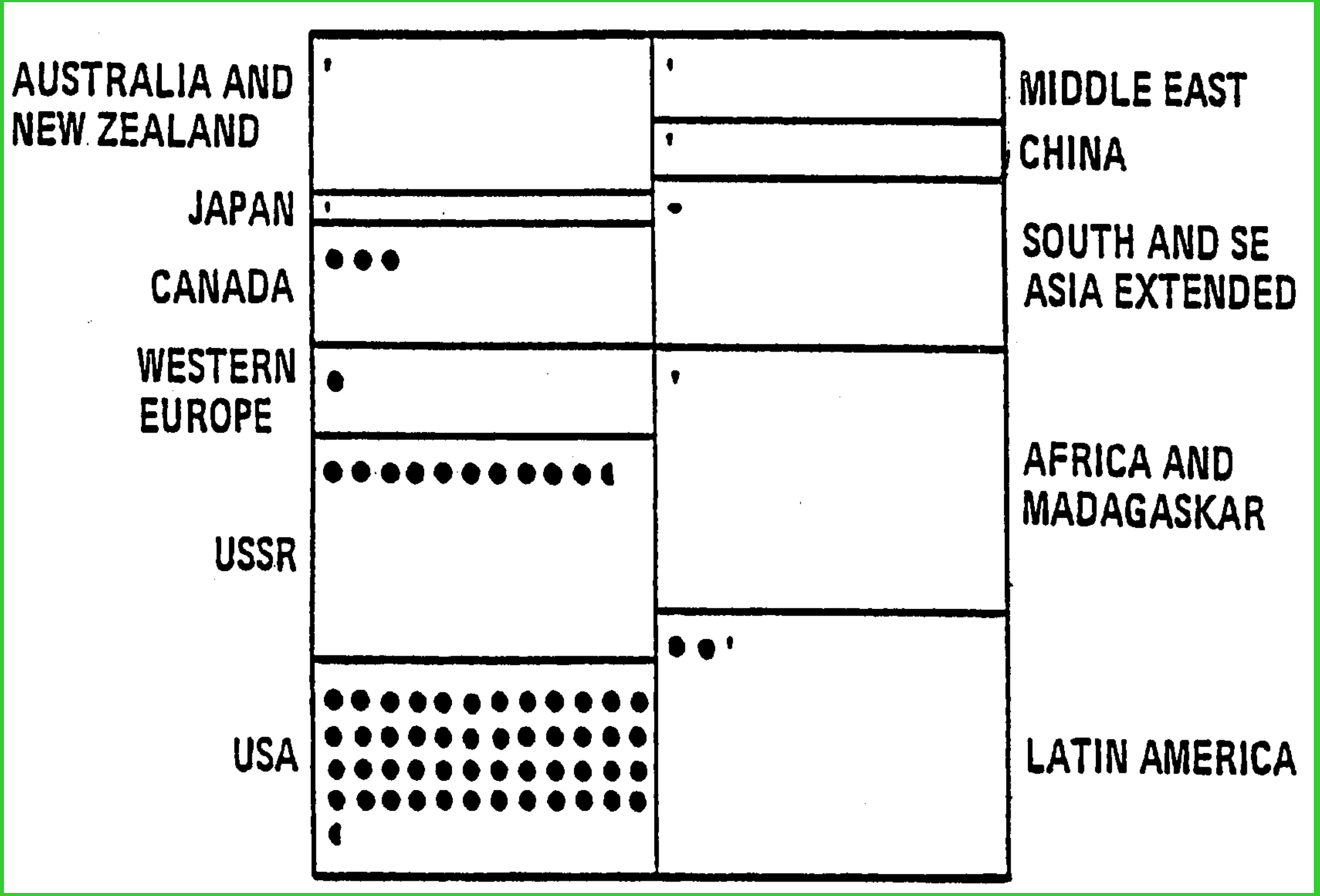
Density of Exploratory Drilling per (potentially petroleum bearing) Sedimentary Area

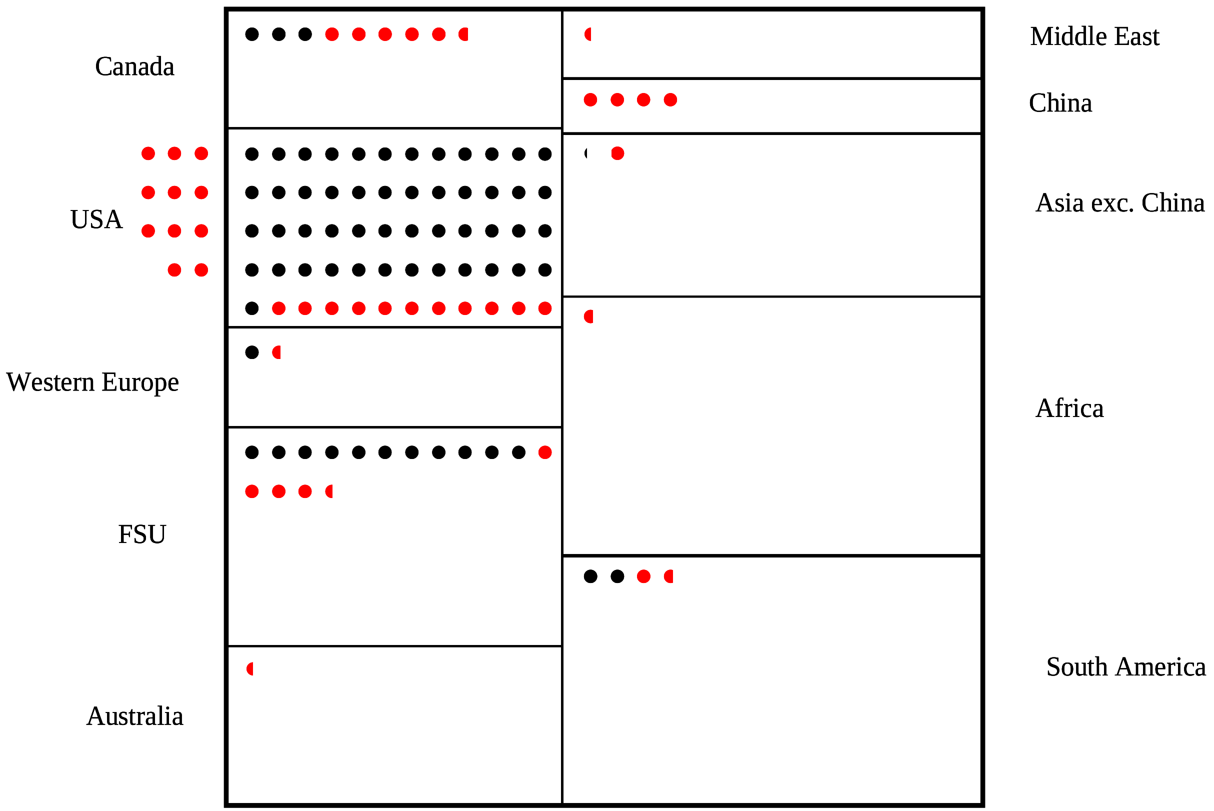
Source: Grossling, 1976



Prospective Sedimentary Areas and Oil Drilling Densities as per 1975 and per 2003

(B. Grossling's "Window on Oil")

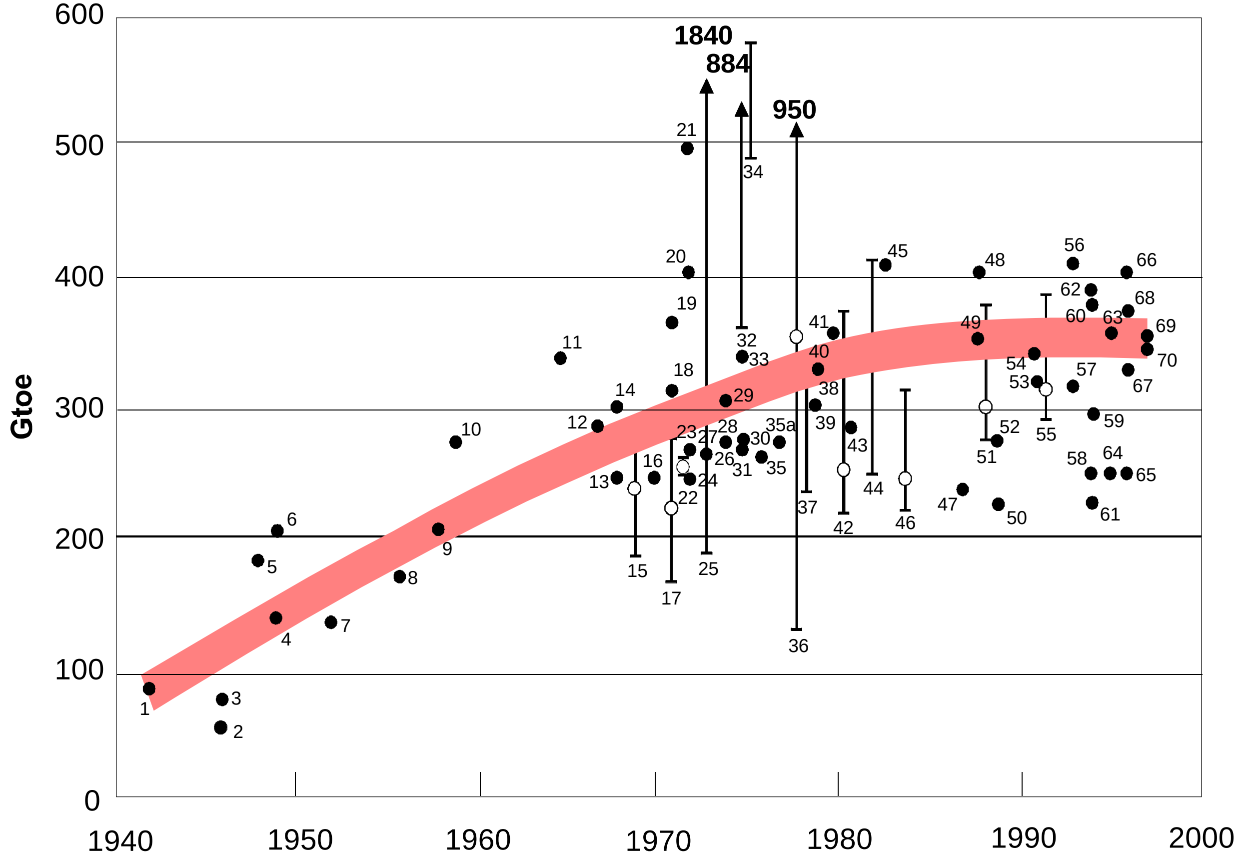
Update courtesy of Jeff Possick, Yale FES 802, 2004



Wells drilled through 1975 shown in black. Wells drilled 1976 through 2003 shown in red.
Each circle represents 50,000 wells. Data through 1975 and relative petroleum prospective area from Grossling: "Window on Oil"
Wells drilled 1976 through 2003 per *World Oil*, August issue 1977 through 2003.
From the 1.9 million wells drilled worldwide since 1975 three quarters were drilled in mature oil provinces (esp. the USA), classified in 1975 as "close to drilling saturation".

Estimates of "ultimately recoverable" Conventional Oil

(*u.r.* = past production + current *reserves* + future discoveries and field growth)



Source: BGR, 1998.

Conventional Oil: Estimates of “ultimately recoverable” Resources

			Gtoe
1	1942	Pratt, Weeks, Stabinger	82
2	1946	Duce	55
3	1946	Poqe	76
4	1948	Weeks (Esso)	183
5	1949	Levorsen	205
6	1949	Weeks	138
7	1953	Mac Naughton	136
8	1956	Hubbert (Shell/USA)	171
9	1958	Weeks (Esso)	205
10	1959	Weeks (Esso)	273
11	1965	Hendricks (USGS)	338
12	1967	Ryman (Esso)	285
13	1968	Shell	246
14	1968	Weeks (Esso)	300
15	1969	Hubbert	184-268 (235)
16	1970	Moody (Mobil)	246
17	1971	Warman (BP)	164-273 (218)
18	1971	Weeks (Esso)	312
19	1971	US National Petroleum Council	364
20	1972	Linden	402
21	1972	Weeks (Esso)	498
22	1972	Moody, Emerick (Mobil	246-259 (253)
23	1972	Richard	266
24	1972	Warman (BP)	245
25	1973	WEC (USGS)	184-1840
26	1973	Wim Vermeer (Shell)	263
26a	1973	Warman (BP)	261
27	1973	Moody & Esser (Mobil) - 9. WPC	277
28	1974	Hubbert (USGS)	272
29	1975	Halbouty 1979 - 10. WPC	304
30	1975	Adams and Kirby (BP)	273
31	1975	Exxon	265
32	1975	Grossling (USGS)	354-884
33	1975	BGR	336
34	1975	Odell	486-576
35	1976	Klemme (Weeks)	259

			Gtoe
35a	1977	Hubert	272
36	1978	WEC	127-950(350)
37	1978	Nehring	231-313
38	1979	Halbouty (Moody) - 10.WPC	304
39	1979	Meyerhoff	300
40	1979	Roorda	330
41	1980	WEC	354
42	1985	Masters et al. - 11. WPC	213-369 (246)
43	1981	Colitti (Agip)	283
44	1982	Exxon	245-408
45	1983	Odell and Rosing	408
46	1984	Masters et al. 1987 - 12. WPC	217-308 (239)
47	1987	Keller (Chevron)	236
48	1988	Deutsche BP	400
49	1988	BGR	350
50	1989	Campbell	224
51	1989	Masters et al. 1991 - 13. WPC	270-371 (295)
52	1989	Bookout	272
53	1991	Montardet and Alazard 1992	318
54	1991	Tedeschi	340
55	1992	Masters et al. 1994 - 14. WPC	285-382 (309)
56	1993	Townes	408
57	1993	BGR 1995	313
58	1994	Laherrere	245
59	1994	Petroconsultants	291
60	1994	Guttiereres	374
61	1994	Campbell 1995	224
62	1994	Edwards 1997	386
63	1995	Mackenzie 1996	354
64	1995	Mabro 1996	245
65	1996	Campbell 1997	245
66	1996	Odell 1998 (Bezug auf Shell)	400
67	1996	Shell	325
68	1996	Schollnberger 1998	370*
69	1997	Hiller 1997	350
70	1997	BGR 1998	341

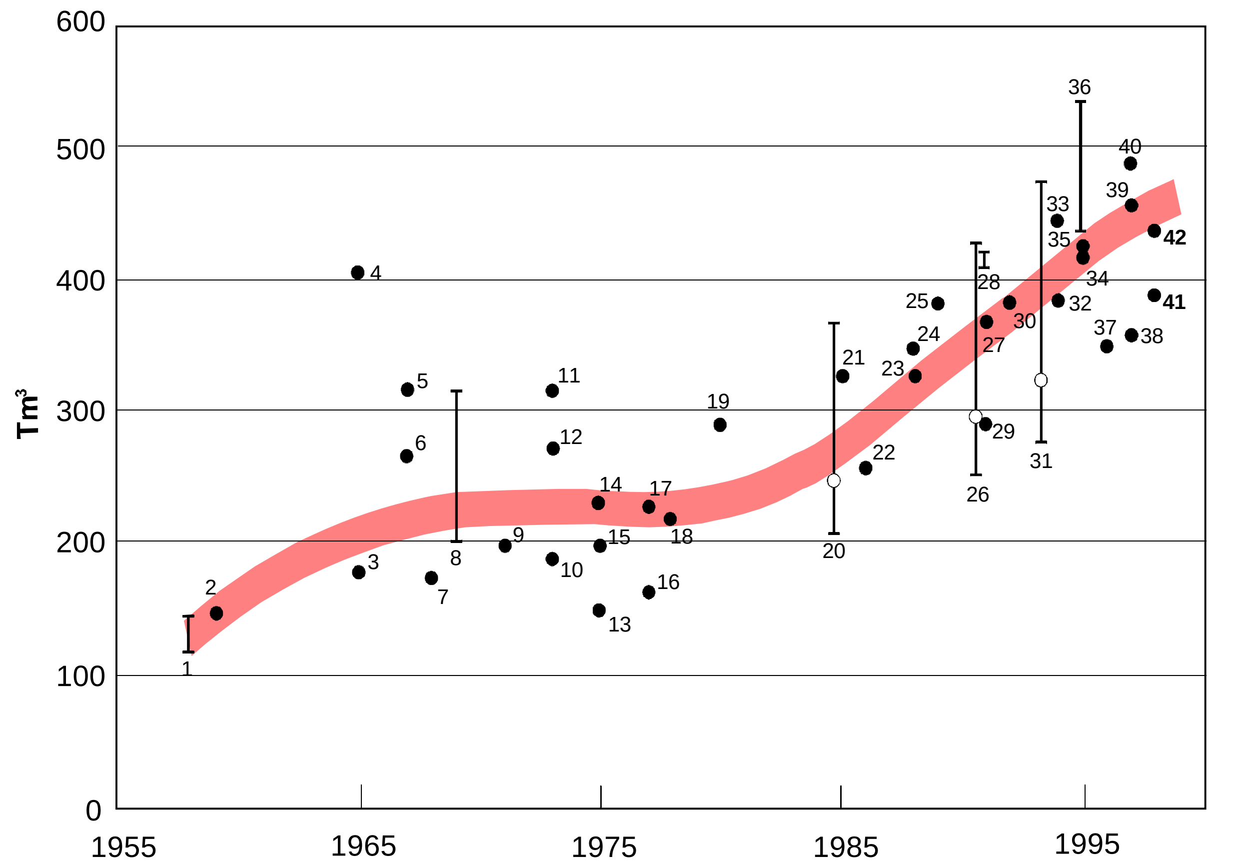
* including heavy oil (78 Gtoe)

Source: BGR, 1998.

USGS Estimates of "ultimately recoverable Reserves" in 1987 and 2002 Data (Source: Masters, 1987; BP, 2002)

	1987 USGS estimates			
	Reserves	Undiscovered 95% probability	Resources 5% probability	Reserves BP 2002
Saudi Arabia	166	20	65	262
Kuwait	73	1	7	96
Oman	5	<1	4	5
Middle East	421	62	199	686

Conventional Gas: Estimates of "ultimately recoverable" Resources



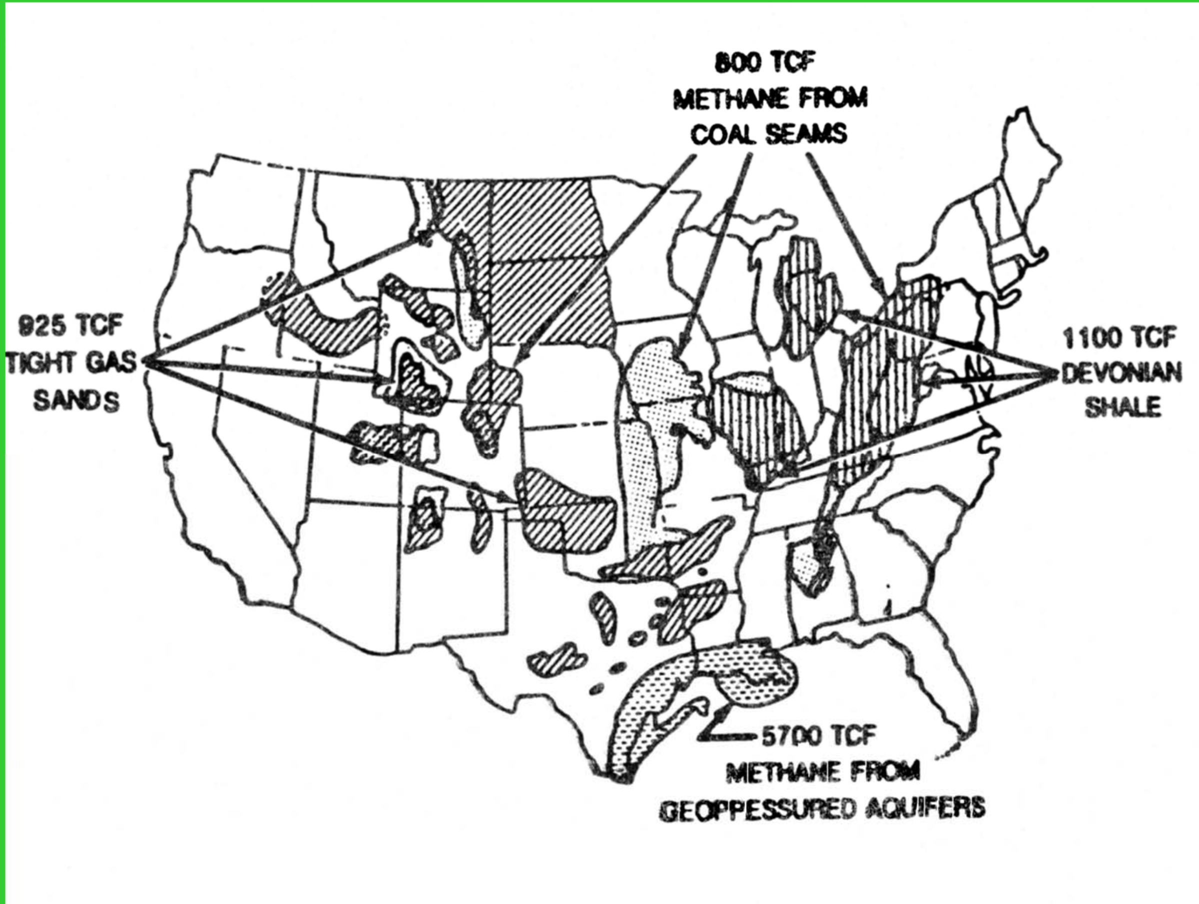
Source: BGR, 1998.

Conventional Gas: Estimates of “ultimately recoverable” Resources

			$10^{12} m^3$
1	1958	Weeks	120-150
2	1959	Weeks	150
3	1965	Weeks	180
4	1965	Hendriks/USGS	410
5	1967	Ryman/Esso	320
6	1967	Shell	270
7	1968	Weeks	175
8	1969	Hubbert	205-320
9	1971	Weeks	200
10	1973	Koppack/Shell	190
11	1973	Hubbert	320
12	1973	Linden	275
13	1975	Adams & Kirkby	150
14	1975	BGR	235
15	1975	Nat. Ac. Science Washington	200
16	1977	IGU #)	165
17	1977	LNG 5., Düsseldorf	230
18	1978	Meyerhoff (10. WPC)	220
19	1980	11. WEK	293
20	1985	Masters (12. WPC)	208-369 (250)
21	1985	IGU (16. WGC)	330
22	1986	Ruhrgas	259
23	1988	Ruhrgas	329
24	1988	IGU (17. WGC)	351
25	1989	BGR	385
26	1991	Masters (13. WPC)	251-430 (297)
27	1991	IGU (18. WGC)	370
28	1991	Krylov (13. WPC)	413-423
29	1991	World Energy Council	292
30	1992	Ruhrgas	386
31	1994	Masters (14. WPC)	277-479 (327)
32	1994	Ruhrgas	387
33	1994	IGU (19. WPC)	449
34	1995	BGR	420
35	1995	Ruhrgas	427
36	1995	Cornot-G./Cedigaz	443-539
37	1996	Colitti & Simeoni	351
38	1997	Mobil	360
39	1997	IGU (20. WGC)	460
40	1997	Enron Corp.	492
41	1998	Schollnberger/AMOCO	390
42	1998	BGR (this study)	439

Source: BGR, 1998.

UNCONVENTIONAL GAS RESOURCES OF UNITED STATES



Methane Hydrates (Clathrates)

Global Hydrocarbon Reserves and Resources in ZJ (10^{21}J)

in ZJ	Production to/in 1860-2005	2005	Reserves	Resources	Other Occurrences
Oil					
Conventional	6.07	0.148	5 - 8	4 - 6	
Unconventional	0.51	0.020	4 - 6	11 - 15	>40
Gas					
Conventional	3.09	0.090	5 - 7	7 - 9	
Unconventional	0.11	0.010	20 - 67	40 - 122	>1000
Coal	6.71	0.124	17 - 21	291 - 435	>140
Total	16.49	0.392	51 - 108	354 -587	>1000

Source: GEA Energy Primer, 2012, Nakicenovic et al., 1996

Global Hydrocarbon Reserves and Resources in ZJ (10^{21}J)

in ZJ	Production to/in 1860-2005	2005	Reserves	Resources	Other Occurrences
Oil					
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Conventional	3.09	0.090	5 - 7	7 - 9	
Unconventional	0.11	0.010	20 - 67	40 - 122	>1000
Coal	6.71	0.124	17 - 21	291 - 435	>140
Total	16.49	0.392	51 - 108	354 -587	>1000

Lowest reserves/resources: conventional oil and gas

Largest occurrence: methane hydrates

Global Hydrocarbon Reserves and Resources in GtC ($GtCO_2$ = x44/12)

in GtC	Production to/in 1860-2005	2005	Reserves	Resources	Other Occurrences
Oil					
Conventional	121	3.0	100 - 160	80 - 120	
Unconventional	10	0.4	8 - 120	220 - 300	>800
Gas					
Conventional	47	1.4	77 - 107	107 -138	
Unconventional	2	0.2	306 - 1025	612 - 1867	>15000
Coal	173	3.2	439 - 542	7508 - 11223	>3600
Total	354	8.1	930 - 1954	8527 - 13648	>19000

Source: GEA Energy Primer, 2012, Nakicenovic et al., 1996

Global Hydrocarbon Reserves and Resources in GtC ($GtCO_2 = x44/16$)

in GtC	Production to/in 1860-2005	2005	Reserves	Resources	Other Occurrences
Oil					
Conventional	121	3.0	100 - 160	80 - 120	
Unconventional	10	0.4	8 - 120	220 - 300	>800
Gas					
Conventional	47	1.4	77 - 107	107 -138	
Unconventional	2	0.2	306 - 1025	612 - 1867	>15000
Coal	173	3.2	439 - 542	7508 - 11223	>3600
Total	354	8.1	930 - 1954	8527 - 13648	>19000

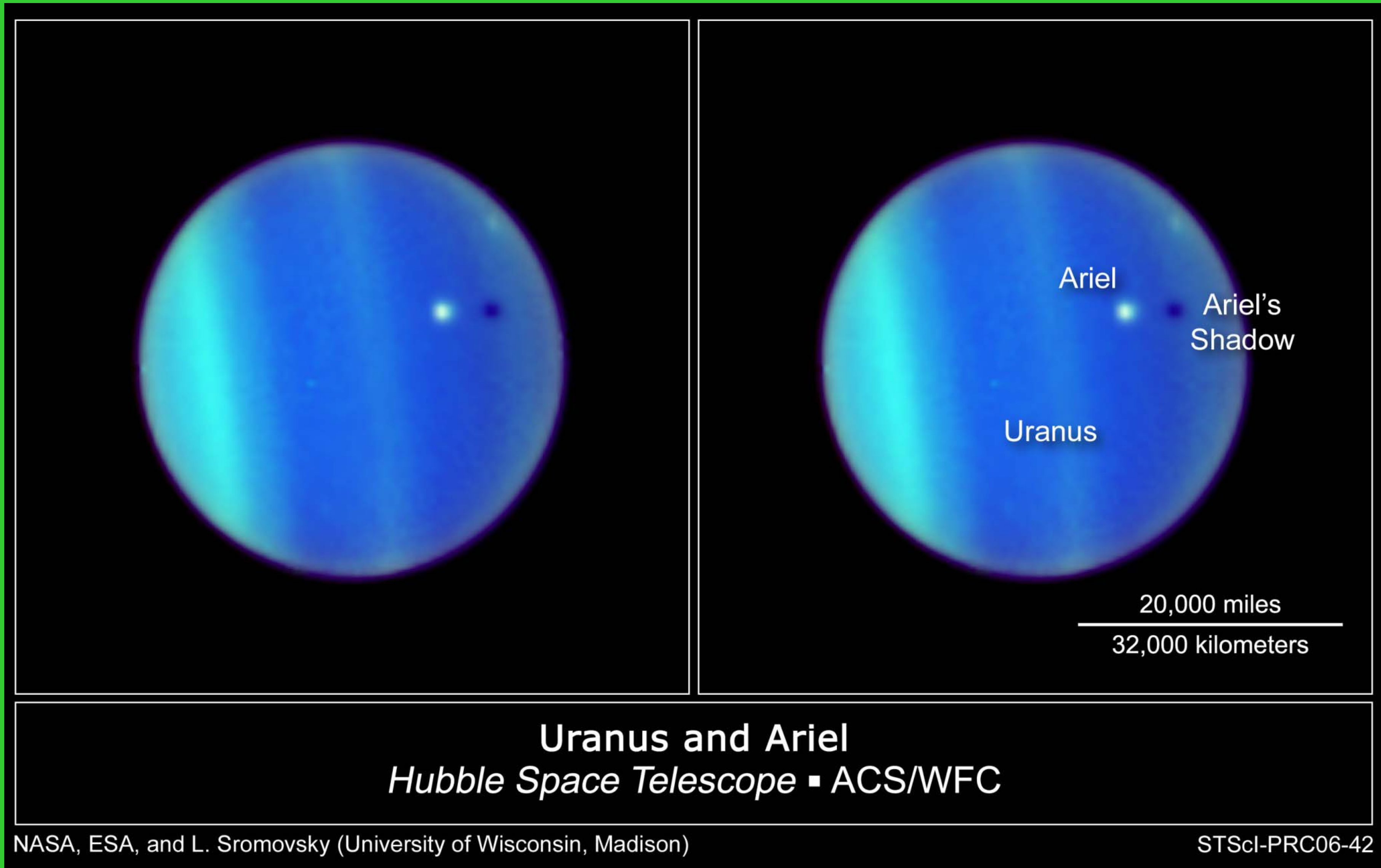
IPCC: “discernible influence on climate system: atmospheric content: 860 GtC, (+240 GtC since 1750)

Remaining carbon budget to stay below 2° C: 300-<1000 GtC

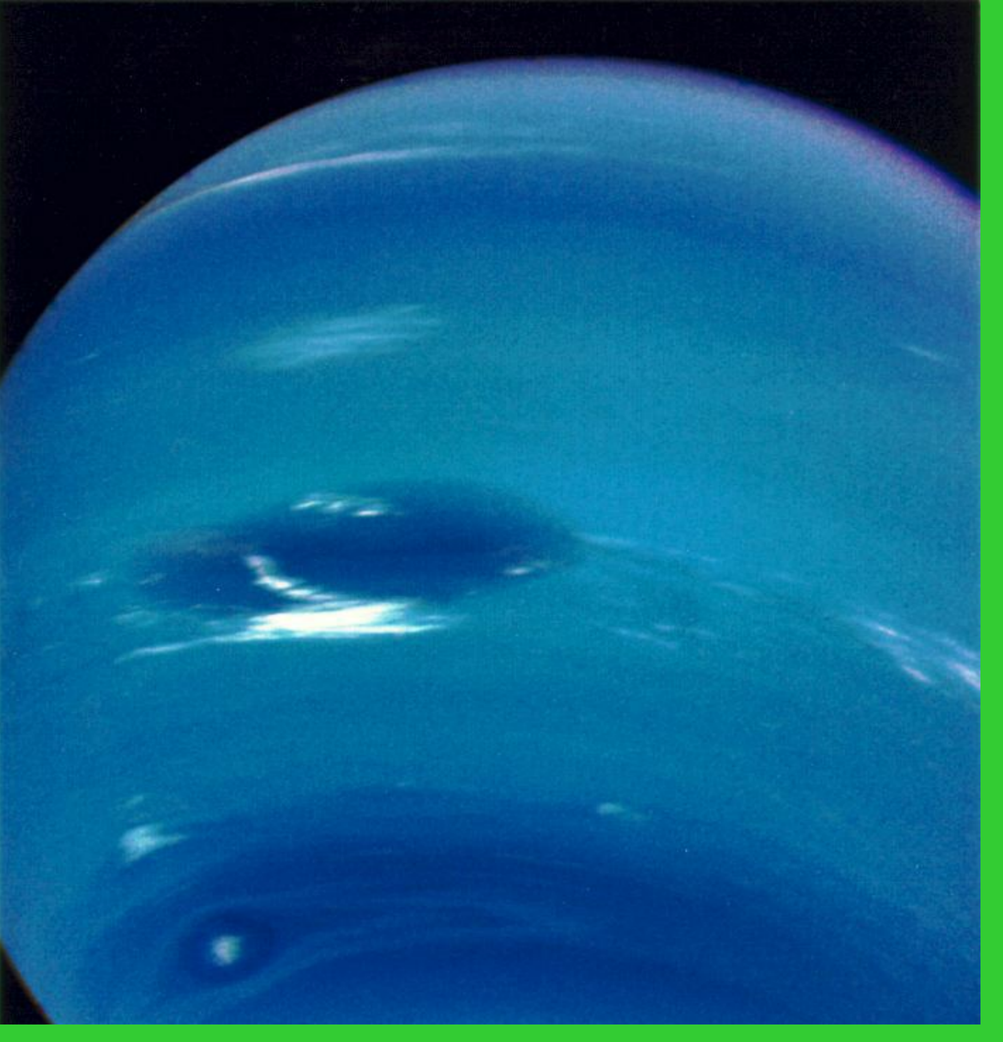
Something Wrong with Theory?

- Historical success rate in US oil/gas drilling: No better than with random drilling
- Depletion of fields postponed: Refill from below: Jean Whelan="state of art"
- Deep gas hypothesis: Tommy Gold=highly controversial
- Gas tracers (C-14): Abiogenic gas=Yes, but minor curiosity?
- Gas hydrates: How to explain quantities and occurrence (e.g. in deep sea bottom)?
- Methane abundance in extraterrestrial environments: Relevance for planet Earth?

Why is Uranus' (or Neptune's) Atmosphere Blue? (Methane=Natural Gas)



Neptune



Renewable Resources

(in ZJ, input equivalent*)

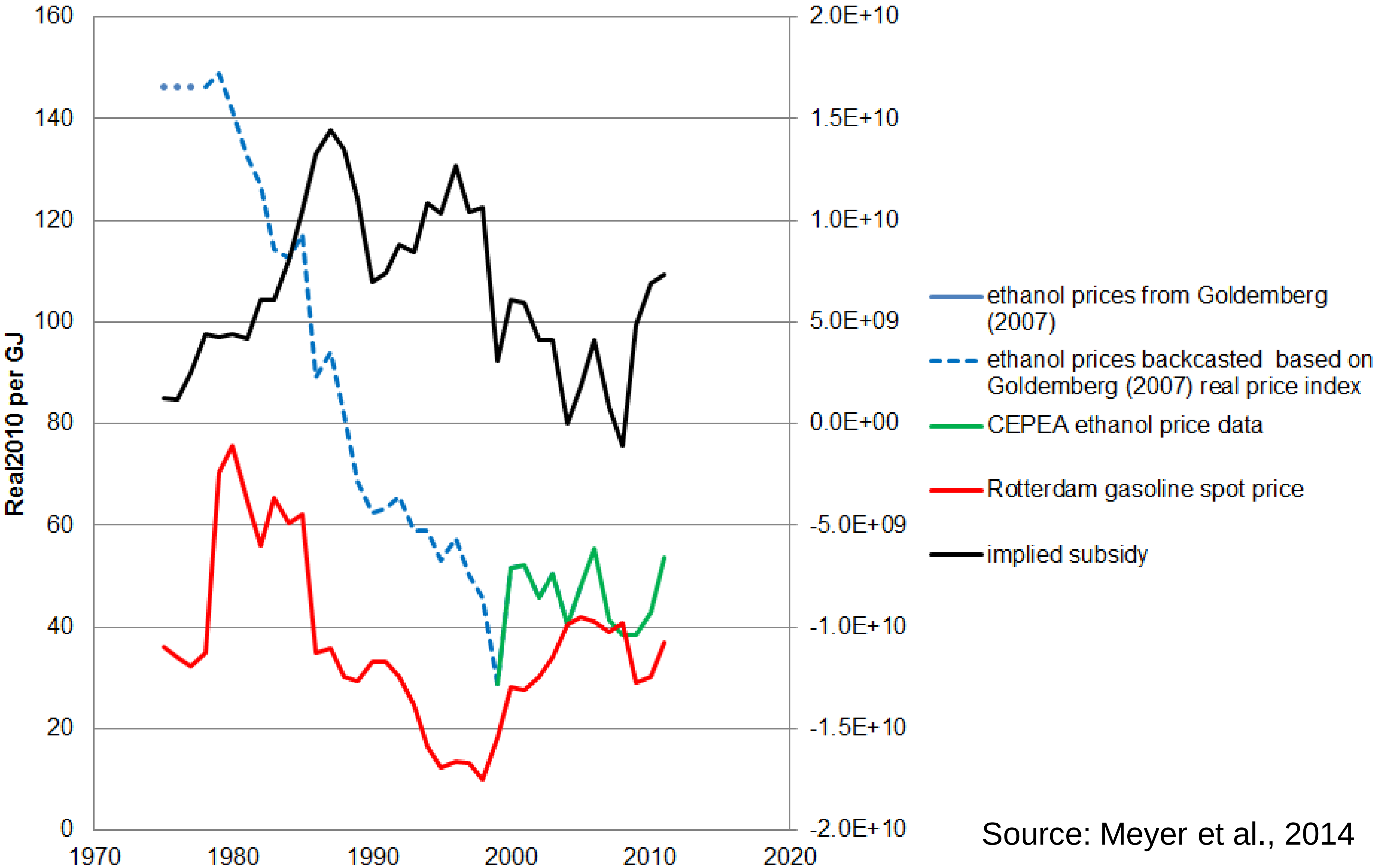
in ZJ	PE input in 2005 "reserves"	technical potential "resources"	Annual flows "occurrences"
Biomass	0.460	.2 - .3	1.3
Geothermal	0.001	.8 - 1.4	1.5
Hydro	0.030	.05 - .06	0.16
Solar	<.001	62 - 280	3900
Wind	0.001	1.3 - 2.3	110
Ocean	-	3.2 - 10.5	1000
Total		70 - 300	5000

*** = renewable flow harvested, [input]. For energy output multiply with efficiency (3 – 90% [ocean – biomass])**

Source: GEA Energy Primer, 2012

Brazil – Ethanol vs. Gasoline and Crude Oil Prices 1975-2011

Note cumulative subsidy of 240 Billion Real or ~140 billion US$



Source: Meyer et al., 2014

A Useful Reminder

The probability of occurrence of predicted energy trends is inversely proportional to the intensity of the underlying consent

(H.R. Linden)

Arnulf Grübler

Zusammenfassung Block 6
(Rohstoffe & Verfügbarkeit)

- **reserves, resources, occurrencies**
- **resources = function of knowledge, economics and technology**
- **Knowledge and economics are dynamic (function of dynamic technology)**
- **orders of magnitude for energy:**
- **reserves: 1200 Gtoe (1000 GtC)**
- **resources: 3300 Gtoe (3000 GtC)**
- **occurrencies:>24000 Gtoe (>13000 GtC)**
- **largest fossil occurrence: methane hydrates**
- **recoverability: concentration, cost dynamics**
- **abundance/scarcity: technologically and economically constructed**