Non-Renewable but Inexhaustible - Resources in an Endogenous Growth Model

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Non-Renewable Resources - A First Approach

2 basic observations:

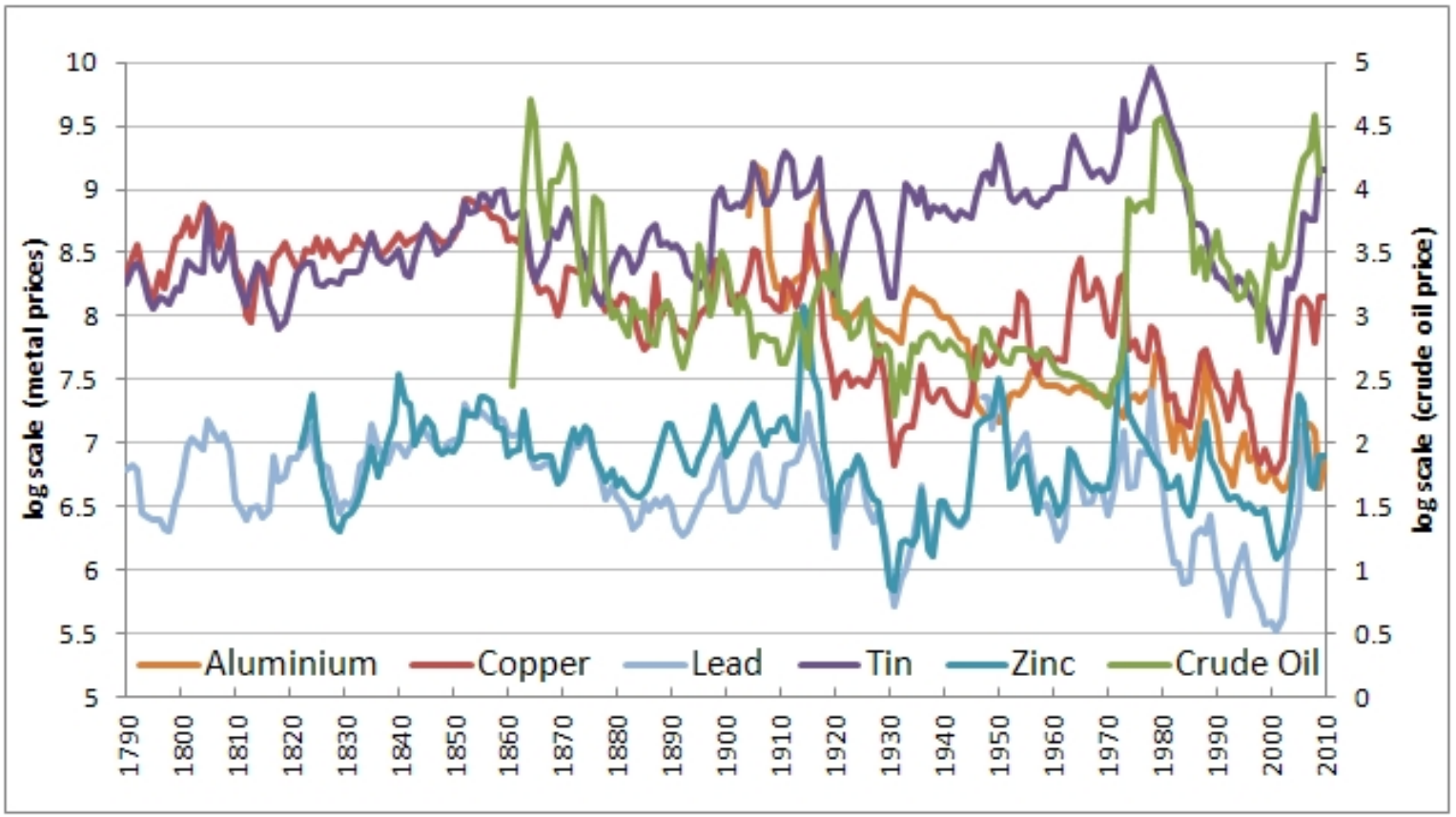
- The supply of a non-renewable resource is finite: $R_t = -\dot{S}_t$
- The world economy grows at an exponential rate

Conclusion (Hotelling (1931)):

- Extraction of the resource declines
- Price of the resource increases (typically at the rate of interest)

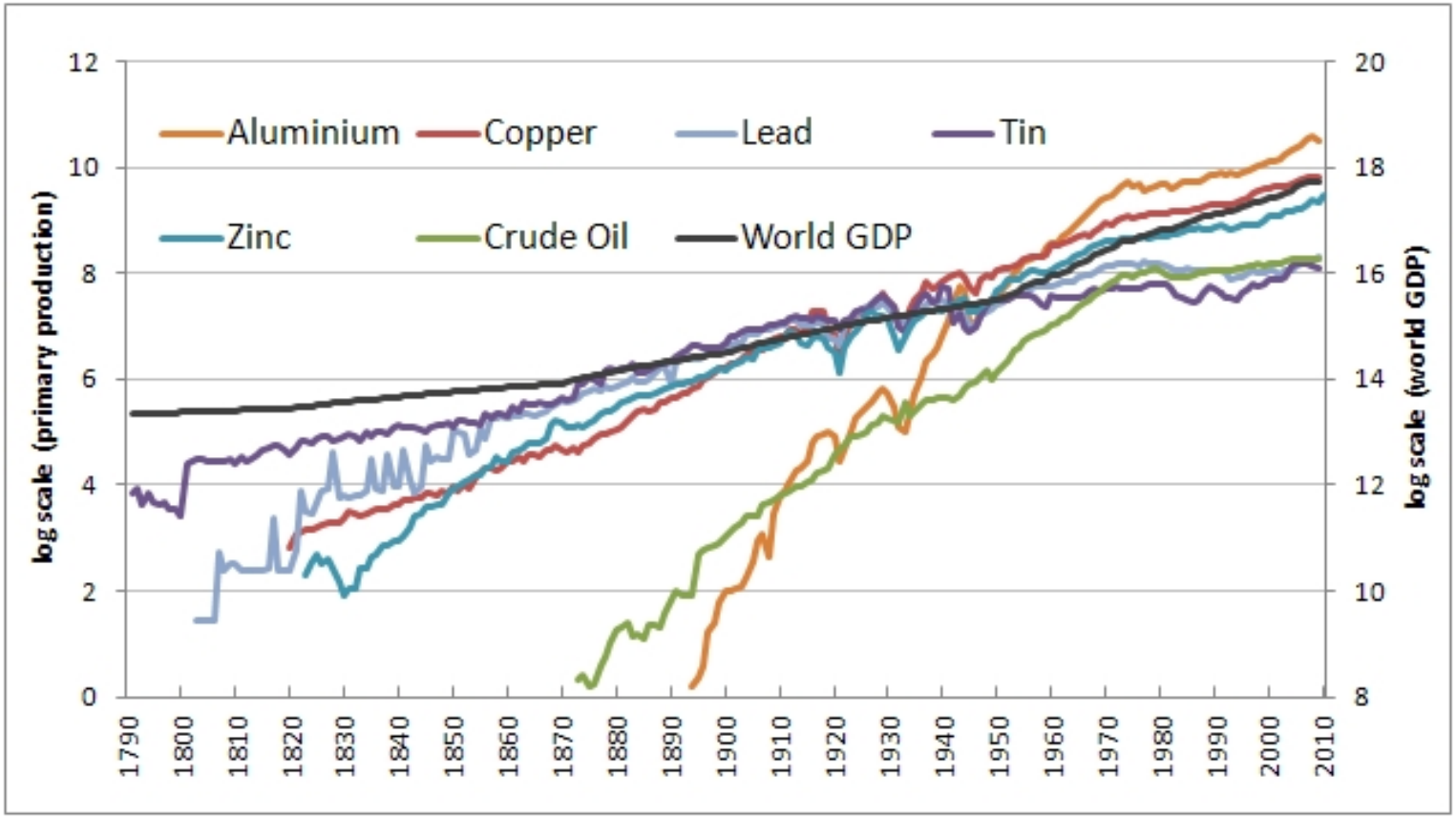
Potential Implication: Limits to growth

Non-renewable resource prices 1790-2010



Real prices of different non-renewable resources in constant 1990-US-Dollar in logs.

World non-renewable resource production and world GDP



World mine production of non-renewable resources and world GDP (secondary x-axis) in logs.

Main Results

- Growth triggers exponentially increasing:
  - investment in innovation of extraction technology
  - use and production of the resource
- Extraction costs determined by trade-off between:
  - innovation in extraction technology, and
  - distribution of the non-renewable resource in the earth's crust.
- In our model the non-renewable resource becomes inexhaustible

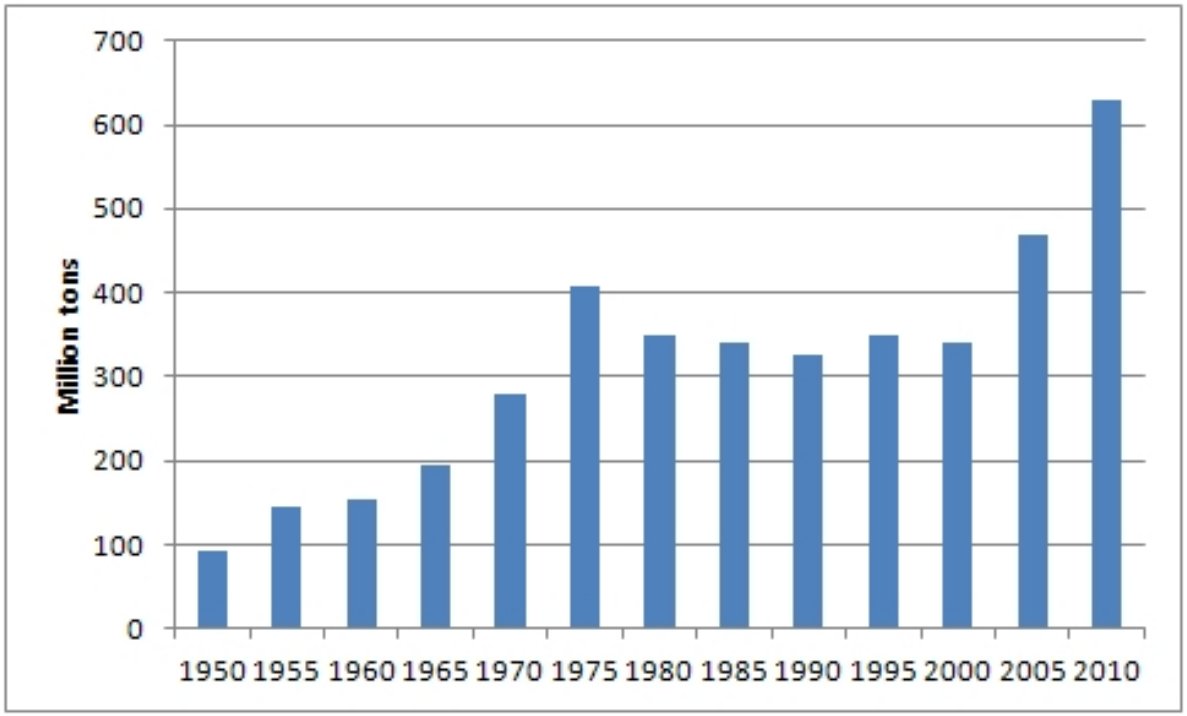
Abundance of selected non-renewable resources

	Reserves/ Annual production (Years)	**Resources/ Annual production** (Years)	**Crustal mass/ Annual production** (Years)
Aluminium	139[a]	263,000[a]	48,800,000,000[bc]
Copper	43[a]	189[a]	95,000,000[ab]
Iron	78[a]	223[a]	1,350,000,000[ab]
Lead	21[a]	362[a]	70.000.000[ab]
Tin	17[a]	"Sufficient"[a]	144.000[ab]
Zinc	21[a]	158[a]	187.500.000[ab]
Gold	20[d]	13[d]	27,160,000[ef]
Rare earth	827[a]	"Very large"[a]	n.a.
Coal	129[g]	2,900[g]	
Oil	55[g]	76[g]	} 1,400,000[i]
Gas	59[g]	410[g]	

Sources: [a] U.S. Geological Survey (2012), [b] Perman et al. (2003), [c] U.S. Geological Survey (2011a), [d] U.S. Geological Survey (2011b), [e] Nordhaus (1974), [f] U.S. Geological Survey (2010), [g] Federal Institute for Geosciences and Natural Resources (2011) [i] Littke and Welte (1992).

- Large amounts of important resources are available in principle

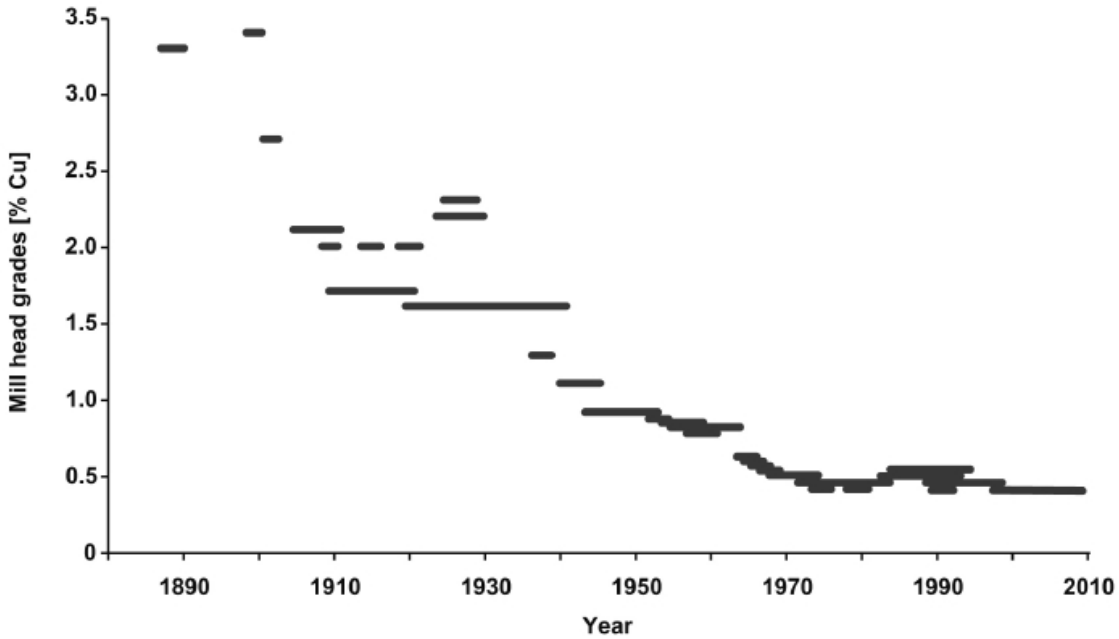
Evolution of Copper Reserves



The Evolution of World Copper Reserves, 1950 - 2010.

- In practice, these resources are accessed

History of Ore Grades Extracted



Historical Development of Mining of Various Grades of Copper in the U.S.

Source: Wagner and Wellmer (2009)

- Technology plays an important role in accessing resources

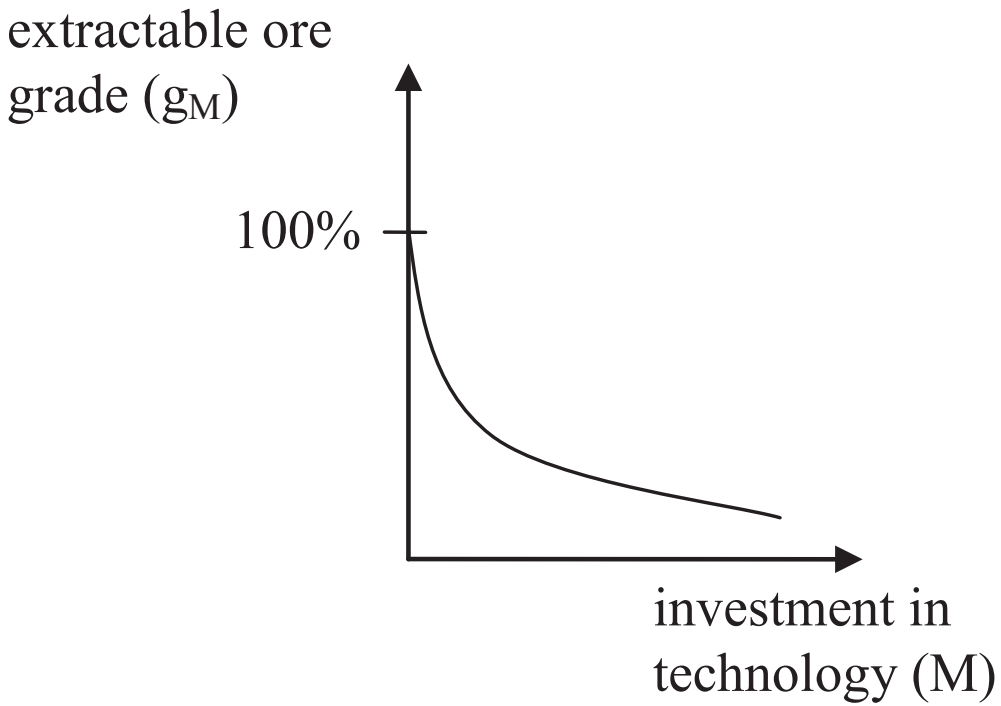
Setup

- Standard Schumpeterian endogenous growth model following Aghion and Howitt (1998)
- One essential non-renewable resource
- Explicit investment in innovation of extraction technology and general innovation
- Price of non-renewable resource = extraction cost + cost of extraction technology

Simplifications:

- No recycling (analogous to extraction?)
- No environmental externalities

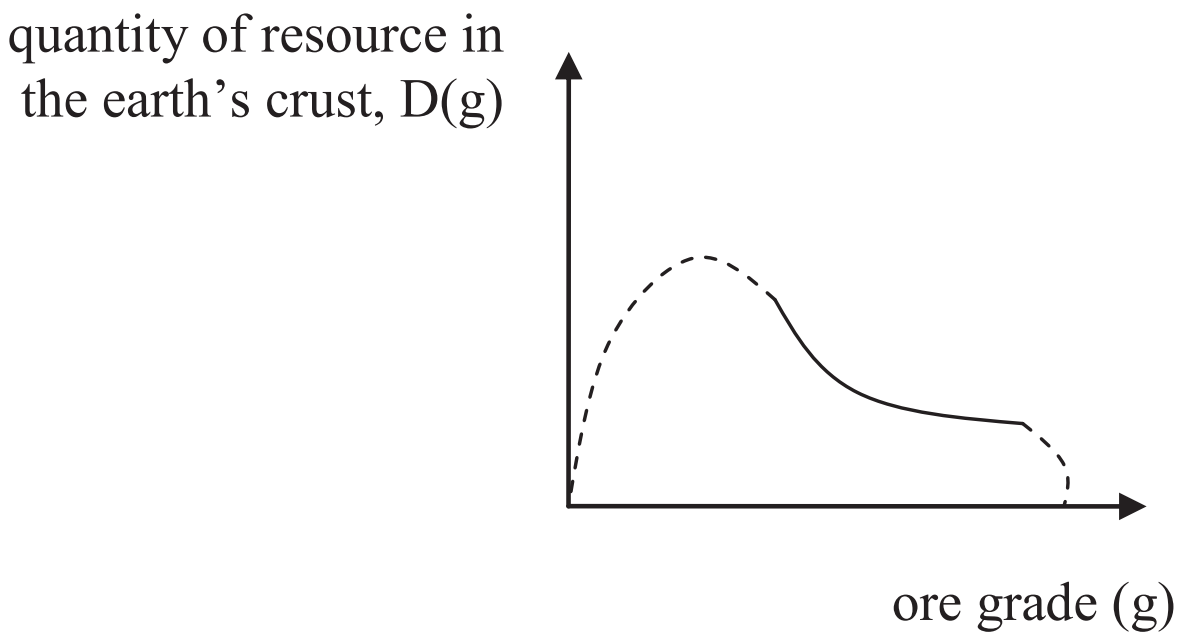
Cost of Innovation in the Extraction Technology



Economically extractable ore grades as a function of accumulated investment in innovation of the extraction technology.

- Functional form: $g_M = \gamma_1 e^{-\gamma_2 M}$

Ore Grade distribution



Non-renewable resource extractable per ore grade.

- Functional form for bold line: $D(g) = -\delta_1 \ln(\delta_2 g)$

Production Function and Results

Production function for final output:

$$Y = K^{\alpha} B^{1-\alpha} L^{\beta} R^{\nu} \quad \text{with } \alpha + \beta + \nu = 1,$$

The change in the capital stock is given as:

$$\dot{K} = Y - C - ER - FS.$$

1. Marginal extraction cost are constant (F constant)
2. Unlocked resources due to innovation in the extraction technology are equal to the extracted resources ($R = S$)
3. Steady state with constant growth rate ($g_K = g_C = g_Y$ constant)
4. Resource extraction grows at the same rate as the economy ($\frac{R}{Y} = \frac{\nu}{E+F}$)

Conclusion

- Empirical evidence:
  - Resource price have no increasing trends in the long run
  - Resource extraction increases (exponentially)
- Economic growth triggers exponentially increasing:
  - investment in extraction technology
  - use and production of non-renewable resources.
- Trade-off between:
  - innovation of extraction technology
  - distribution of resource in the earth's crust.
- Given technological progress: inexhaustibility for foreseeable future, no limits to growth possible
- Core problem: not resource availability, but externalities

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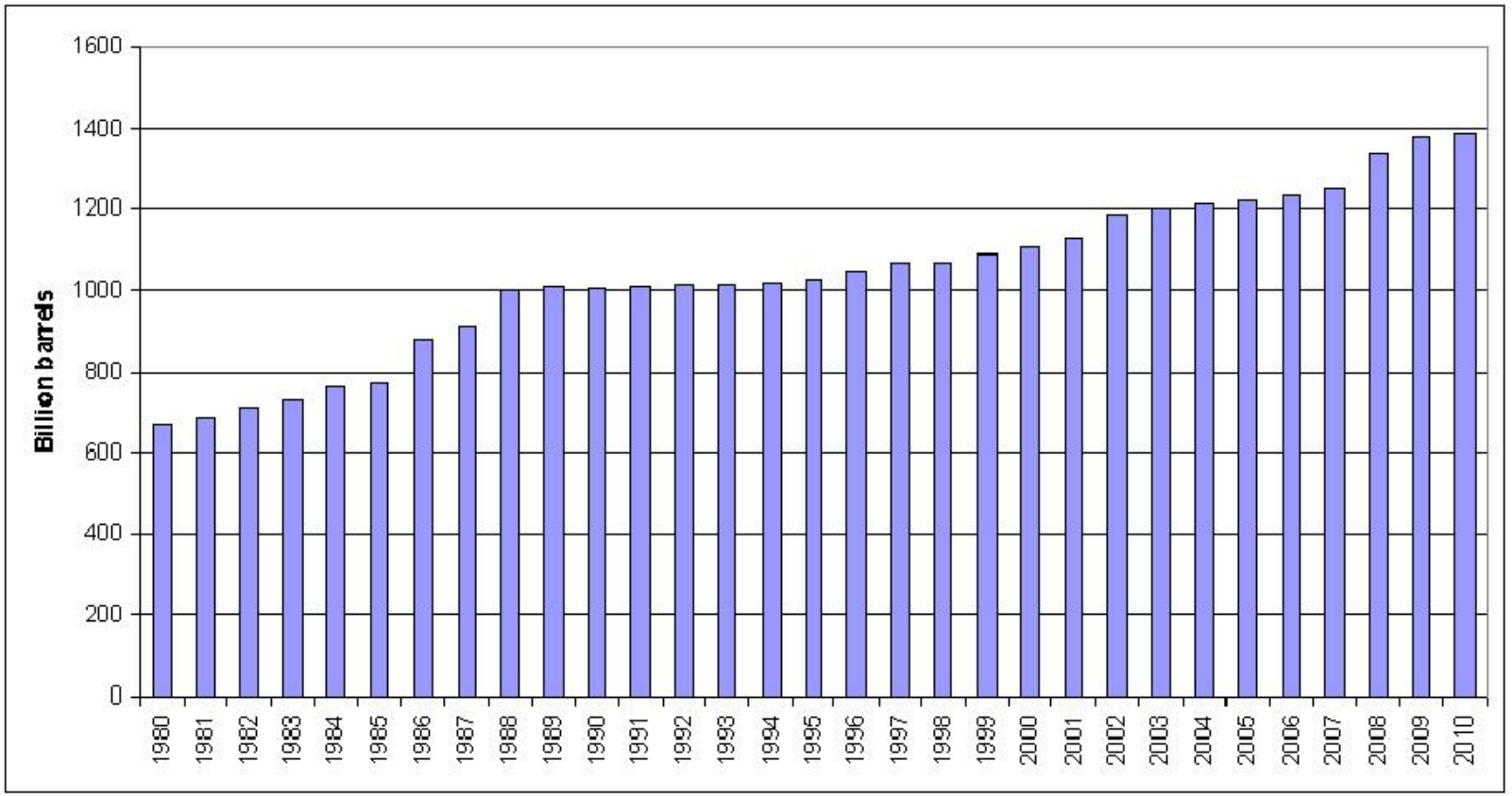
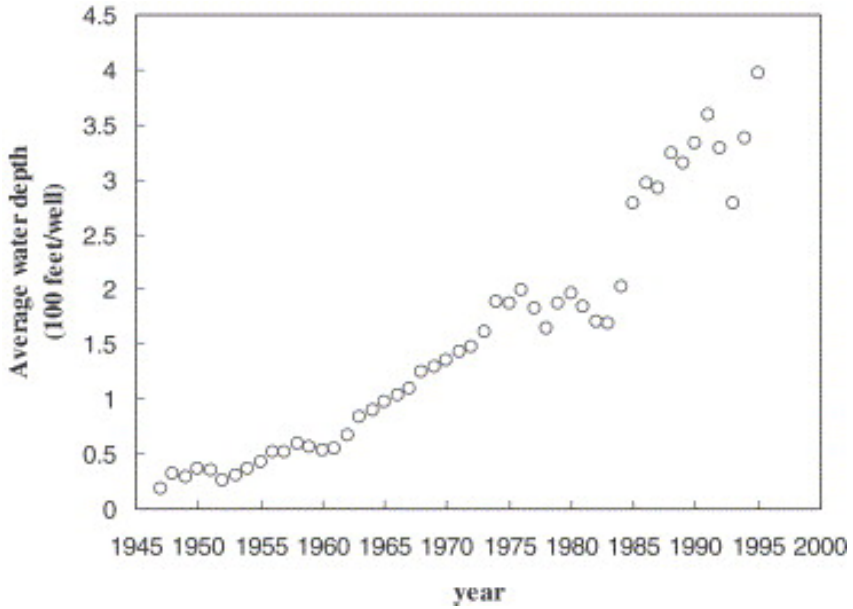
Historical evolution of oil reserves



Historical evolution of world reserves of conventional oil (Source: British Petroleum, 2011).

- In practice, these resources are accessed

Historical evolution of oil reserves



Average Water Depth of Wells Drilled in the Gulf of Mexico

- Technology plays an important role in accessing resources
- Important example: Coal liquefaction (producing synthetic liquid fuels from coal)

Definitions

Reserves: "That part ... which could be economically extracted or produced at the time of determination."

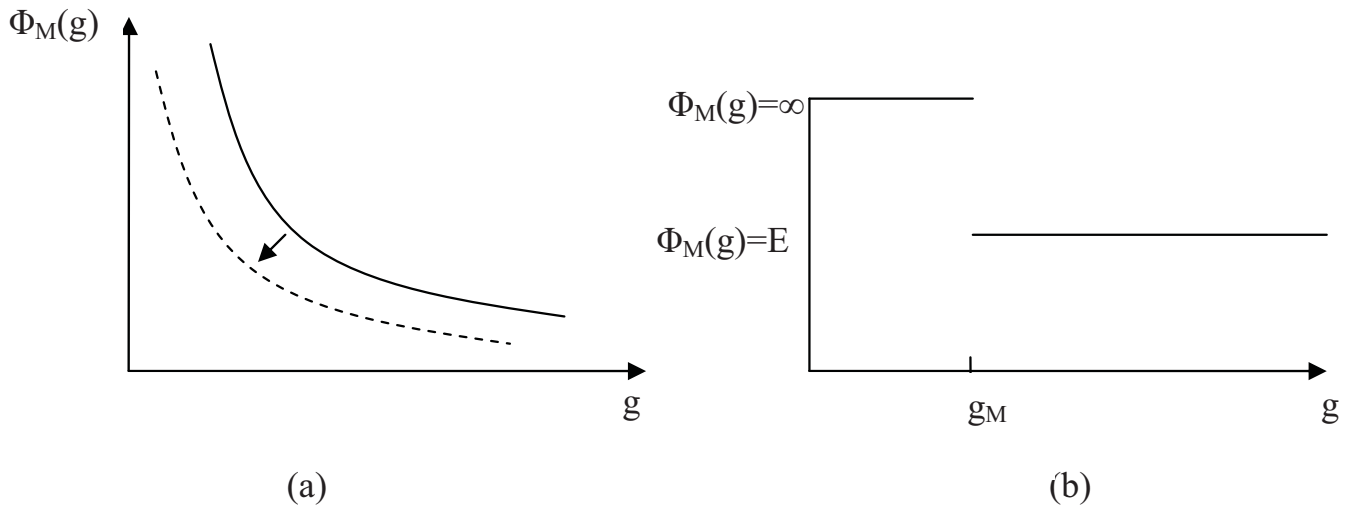
Resources: "A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible ."

Other occurrences: "Materials that are too low grade or for other reasons are not considered potentially economic."

"... the boundary between subeconomic and other occurrences ... is obviously uncertain..."

Source: US-Geological Survey, 2011, p. 193-4.

Extraction Cost



Extraction cost in general (a) and simplified (b)

Resource extraction cost depends on

- state of technology
- difficulty of extraction
- mayor determinant of difficulty of access: ore grade