Finite Resources and the World Economy

John Hassler, Per Krusell, and Conny Olovsson
IIES, IIES, and Sveriges Riksbank/ECB

June, 2021

General motivation

The world economy is dependent on scarce, finite resources:

- Oil and other fossil fuels
- Metals
- Other resource stocks (the climate, etc.)

Our broad focus here:

- how have our world markets dealt with these constraints?
- how will they deal with them in the future?

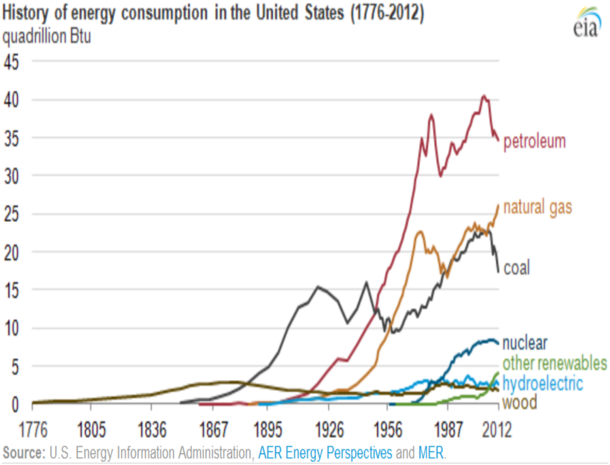
Concrete aim: build toward quantitative macro theory that can help us address these questions. Specific requirements: the model should

- account quantitatively for historical data
- be useful for quantitative (RBC/NK-style) analysis of short-run fluctuations, while building on reasonable long-run path.

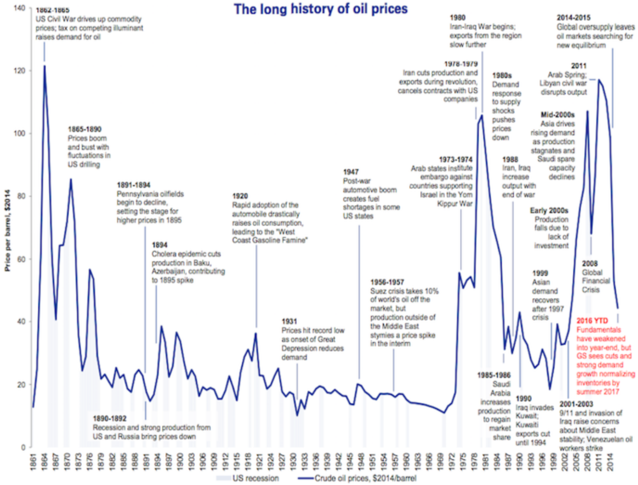
Some pictures of fluctuations

- massive fluctuations in prices of raw materials; special focus on energy supply and the role of fossil fuel
- fossil/oil picture: price and cost-share movements
- per-capita fossil/oil use

U.S. energy consumption



Oil prices


The long history of oil prices
Price per barrel, $2014
1862-1865
US Civil War drives up commodity prices; tax on competing illuminant raises demand for oil
1865-1890
Prices boom and bust with fluctuations in US drilling
1891-1894
Pennsylvania oilfields begin to decline, setting the stage for higher prices in 1895
1894
Cholera epidemic cuts production in Baku, Azerbaijan, contributing to 1895 spike
1890-1892
Recession and strong production from US and Russia bring prices down
1920
Rapid adoption of the automobile drastically raises oil consumption, leading to the "West Coast Gasoline Famine"
1931
Prices hit record low as onset of Great Depression reduces demand
1947
Post-war automotive boom creates fuel shortages in some US states
1956-1957
Suez crisis takes 10% of world's oil off the market, but production outside of the Middle East stymies a price spike in the interim
1973-1974
Arab states institute embargo against countries supporting Israel in the Yom Kippur War
1978-1979
Iran cuts production and exports during revolution, cancels contracts with US companies
1980
Iran-Iraq War begins; exports from the region slow further
1980s
Demand response to supply shocks pushes prices down
1985-1986
Saudi Arabia increases production to regain market share
1988
Iran, Iraq increase output with end of war
1990
Iraq invades Kuwait; Kuwaiti exports cut until 1994
1999
Asian demand recovers after 1997 crisis
Early 2000s
Production falls due to lack of investment
Mid-2000s
Asia drives rising demand as production stagnates and Saudi spare capacity declines
2001-2003
9/11 and invasion of Iraq raise concerns about Middle East stability; Venezuelan oil workers strike
2008
Global Financial Crisis
2011
Arab Spring; Libyan civil war disrupts output
2014-2015
Global oversupply leaves oil markets searching for new equilibrium
2016 YTD
Fundamentals have weakened into year-end, but GS sees cuts and strong demand growth normalizing inventories by summer 2017
US recession
Crude oil prices, $2014/barrel

Energy shares and prices

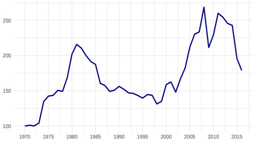


Figure: **The real price of a unit (Btu) of energy, U.S.**

Average real (using a GDP deflator) price of a Btu for the U.S., including all energy sources. **Source:** US Energy Information Administration.

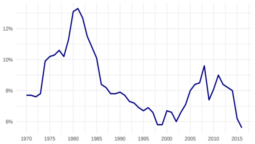
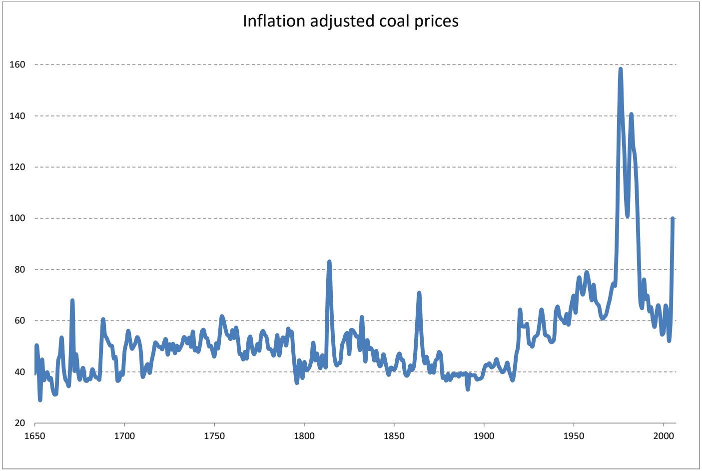


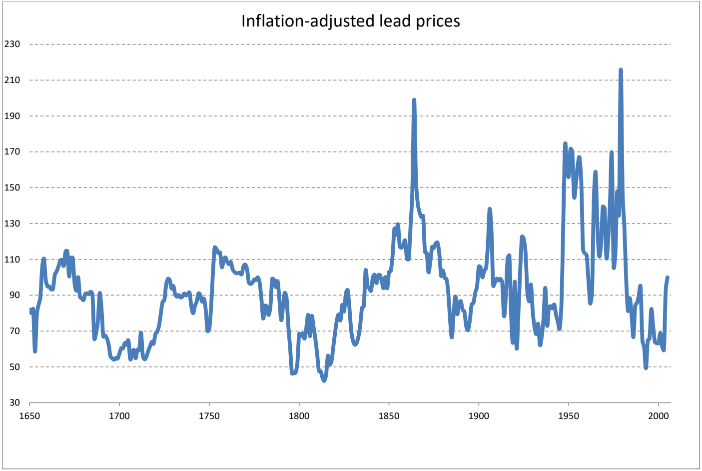
Figure: **The energy share in the U.S.**

The total nominal energy bill divided by nominal GDP. **Source:** US Energy Information Administration.

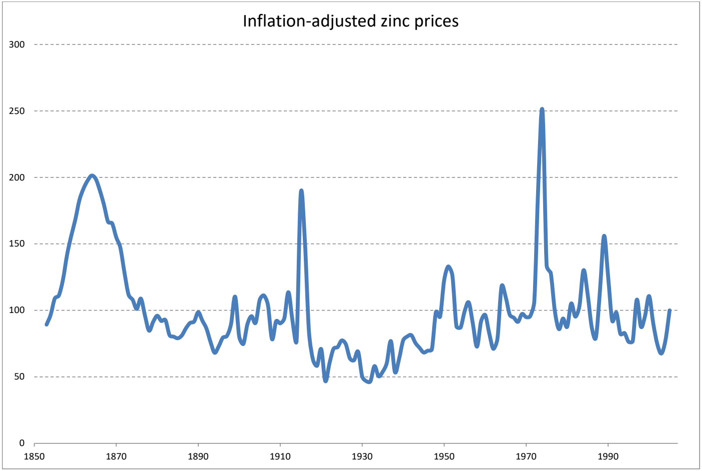
Coal prices


Inflation adjusted coal prices
160
140
120
100
80
60
40
20
1650
1700
1750
1800
1850
1900
1950
2000

Lead prices

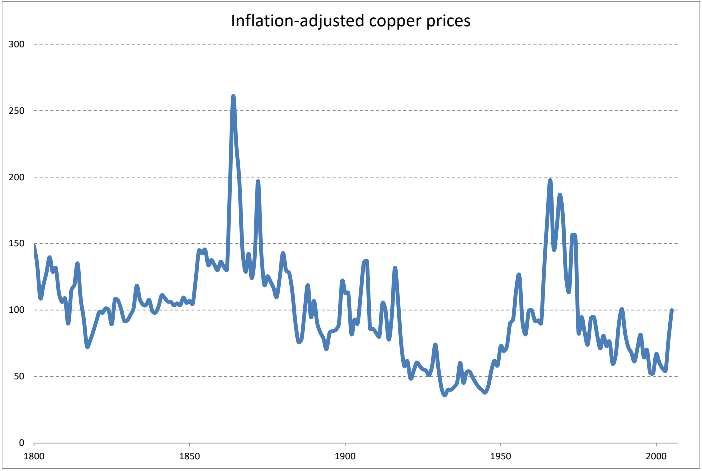

Inflation-adjusted lead prices
230
210
190
170
150
130
110
90
70
50
30
1650
1700
1750
1800
1850
1900
1950
2000

Zinc prices

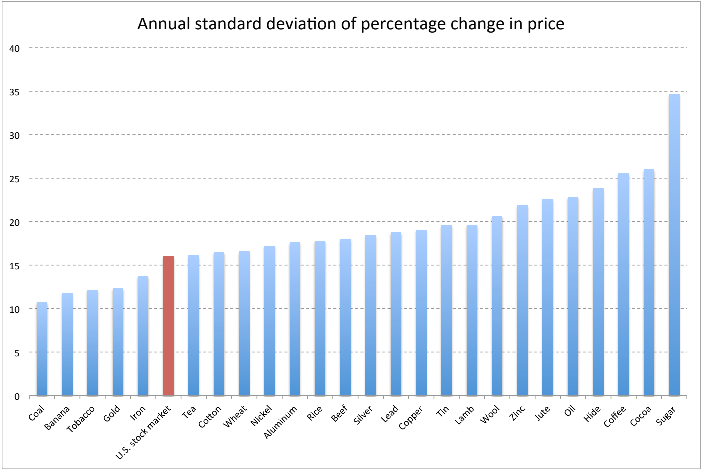


Inflation-adjusted zinc prices
300
250
200
150
100
50
0
1850
1870
1890
1910
1930
1950
1970
1990

Copper prices



Price volatilities



Building toward a framework

Desirable components:

- market mechanisms to deal with scarcity:
  - price movements (massive in short run, trends less obvious)
  - fairly stable shares over longer run
  - endogenous technology as a second market response
- something generating persistently increasing resource use over time

Outline:

- show challenges in generating increasing resource use
- employ a quantitative framework building on Dasgupta and Heal's 1974 workhorse model
- ... in a version with directed input-saving technical change analyzing U.S. data (our recent forthcoming paper)
- applying and further developing this framework for the question at hand here: a world equilibrium model.

Simple theory 1: cake eating

Consider planning problem under zero extraction costs.

$$\max_{\{c_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log c_t$$

subject to

$$\sum_{t=0}^{\infty} c_t = R$$

Solution: $c_t = (1-\beta)R_t$, where $R_{t+1} = R_t - c_t$.

Implies $c_t = (1-\beta)\beta^t R_0$.

We can think of this as R being oil with a production function of final output that is linear in oil.

Simple theory 2: production

Consider planning problem, Cobb-Douglas and $\delta = 1$. Also cake-like.

$$\max_{\{c_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log c_t$$

subject to

$$c_t + k_{t+1} = Ak_t^{\alpha} e_t^{\nu}$$

and

$$\sum_{t=0}^{\infty} e_t = R.$$

Solution: $e_t = (1-\beta)R_t$, where $R_{t+1} = R_t - e_t$. Hence $e_t = (1-\beta)\beta^t R_0$.

Also: $k_{t+1} = \alpha\beta A k_t^{\alpha} e_t^{\nu}$. Gross capital (and output and consumption) growth g constant: $g = g^{\alpha}\beta^{\nu} = \beta^{\frac{\nu}{1-\alpha}} < 1$.

Simple theory 3: adding technology growth

$$\max_{\{c_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log c_t$$

subject to

$$c_t + k_{t+1} = A\gamma^t k_t^{\alpha} e_t^{\nu}$$

and

$$\sum_{t=0}^{\infty} e_t = R.$$

Solution: $e_t = (1-\beta)R_t$, where $R_{t+1} = R_t - e_t$. Hence $e_t = (1-\beta)\beta^t R_0$.

Also: $k_{t+1} = \alpha\beta A\gamma^t k_t^{\alpha} e_t^{\nu}$. Gross capital growth g constant:
$g = \gamma g^{\alpha}\beta^{\nu} = (\gamma\beta^{\nu})^{\frac{1}{1-\alpha}}$. For large enough γ, $g > 1$.

Pricing: Hotelling

Hotelling (1931)'s general insights:

$$p_t - mc_t = \frac{p_{t+1} - mc_{t+1}}{1 + r_t}.$$

This implies

$$\frac{p_{t+1}}{p_t} = 1 + r_t + \frac{1}{p_t}\left(mc_{t+1} - (1 + r_t)mc_t\right)$$

so that if the marginal cost is rising faster than the rate of interest, the price has to rise faster to compensate.

These insights apply above, with $mc = 0$.

Much discussed equation. Viewed not to match data well for oil at least. However, at least in the postwar period, it is not so easy to reject Hotelling (there has been average price growth).

Taking stock

Let's focus on oil.

- Average price growth not too far from the interest rate.
- But why so volatile?
- And why the upward trend in use?

Our path forward:

- Depart from Cobb-Douglas in oil: very low substitutability with other inputs in the short run.
- At longer horizons, more substitutability; model with endogenous directed technical change.
- Can deliver a protracted upward trajectory of oil use (eventually to turn, of course, given the finiteness of the resource).

The price-share evidence again

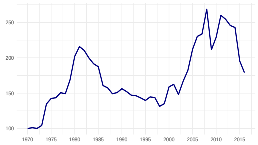


Figure: **The real price of a unit (Btu) of energy, U.S.**

Average real (using a GDP deflator) price of a Btu for the U.S., including all energy sources. **Source:** US Energy Information Administration.

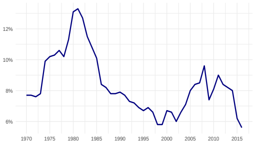


Figure: **The energy share in the U.S.**

The total nominal energy bill divided by nominal GDP. **Source:** US Energy Information Administration.

Cobb-Douglas? No! Leontief appears a much better approximation.

A more reasonable formulation

Instead consider a CES as follows:

$$y \equiv F\left(Ak^{\alpha}l^{1-\alpha}, A_e e\right) = \left[(1-\gamma)\left(Ak^{\alpha}l^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma\left(A_e e\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}.$$

A special case is Leontief ($\varepsilon = 0$): $y = \min\left\{Ak^{\alpha}l^{1-\alpha}, A_e e\right\}$. This fits the above data really well.

Near-Leontief makes the economy very vulnerable to fossil-fuel shortages. This was suggested (and commonly believed) to have caused the worldwide productivity slowdown in the 1970s: it occurred just after the first oil shock hit.

Nice basis for world macro modeling!

Responses to shortages: beyond price hikes

Assume

$$y = F(x_1, x_2; A_1, A_2) = \left[(1-\gamma)(A_1 x_1)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma\,(A_2 x_2)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}$$

$$\text{and} \qquad G(A_1, A_2) = A,$$

with A given but A_1 and A_2 endogenous: *directed* technical change.

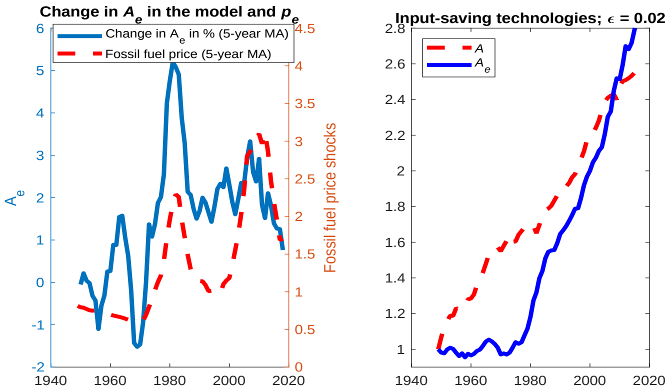
What is the "reduced-form" production function $y = \tilde{F}(x_1, x_2)$ after technology has been directed optimally, given (x_1, x_2)?

Key point: $\tilde{F}$ has higher input substitutability than F. In earlier paper we

- made this point, with focus on long-run fossil share
- documented the implied (backed-out) paths for (A, A_e), speaking strongly in favor of directed technical change.

Here: show this setting gives secularly rising resource use.

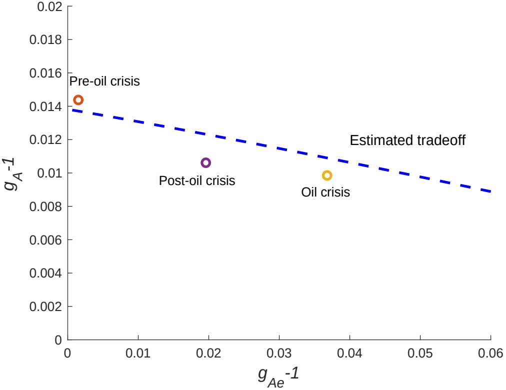
Input-saving technology series



Back out technology series from first-order conditions for firms' input use (and observations on input quantities and prices). Notice:

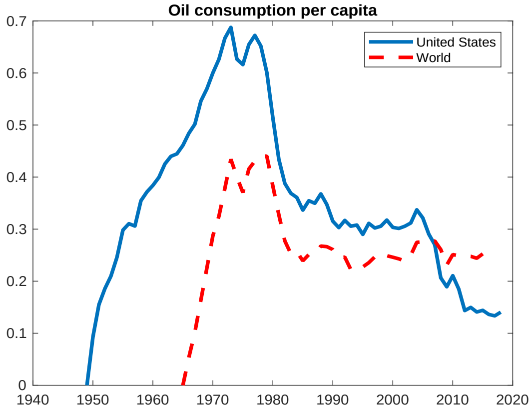
- input saving responds to scarcity (as measured by price);
- A_e dormant until oil shocks hit.

Input-saving technology: medium-run growth rates



Illustrates tradeoff between g_A and g_{A_e} and allows estimation of frontier, as given by G.

Documenting increasing resource use again



"Peak oil" around 1980.

Addressing increasing resource use

Idea: as a stylized example, consider the Leontief case $y = \min\left\{Ak^{\alpha}l^{1-\alpha}, A_e e\right\}$.

- Initially, e is "abundant": A_e, together with the available amount of the resource, R, is high relative to $Ak^{\alpha}l^{1-\alpha}$.
- Hence, there will be a phase where
  - k is accumulated
  - A is built, at the expense of advances in A_e
  - and, so, as a result, e is gradually increasing so that $A_e e$ rises along with $Ak^{\alpha}l^{1-\alpha}$.
- Eventually, of course, e becomes scarce and its use declines, like in the basic cake-eating models.

Core model: equations

Maximize, by choice of $\{c_t, k_{t+1}, e_t, A_{t+1}, A_{e,t+1}, n_t\}_{t=0}^{\infty}$,

$$\sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\sigma} - 1}{1-\sigma} \quad \text{subject to}$$

$$c_t + k_{t+1} = F\left(A_t k_t^{\alpha} l^{1-\alpha}, A_{e,t} e_t\right) + (1-\delta) k_t,$$

where F is the CES above,

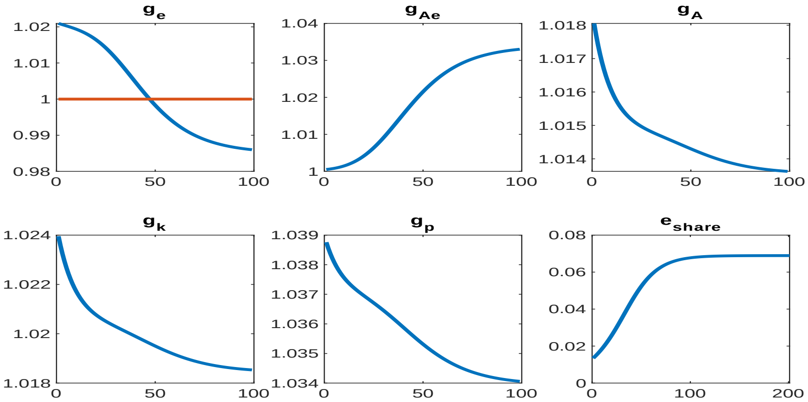
$$\sum_{t=0}^{\infty} e_t = R,$$

$$A_{t+1}/A_t \equiv g_{A,t} = f(n_t),$$

and

$$A_{e,t+1}/A_{et} \equiv g_{A_e,t} = f_e(1-n_t).$$

Results, core model



Oil use increases for about 50 years, while growth of A_e is close to zero for two decades; growth in A and capital initially strong and then falls.

Extended model

Idea here: "green" technology will finally take over. What is the path there?

Replace e with CES in e_1—oil, with a restriction as above—and

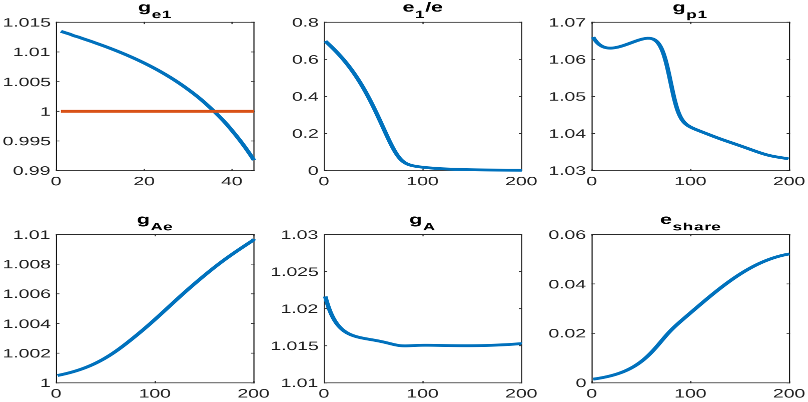
- e_2, which is produced using output units
- and subject to decreasing returns ($\chi > 1$, "land" being a scarce factor); otherwise same production technology as used for output
- and assume that *CES* does not allow endogenous technology and has substitution elasticity ρ higher than one (more than Cobb-Douglas).

$$c_t + k_{t+1} = F\left(A_t k_t^{\alpha} l^{1-\alpha}, A_{e,t} e_t\right) + (1-\delta) k_t - B e_{2,t}^{\chi}$$

$$e_t = \left[(1-\lambda)\, e_{1,t}^{\frac{\rho-1}{\rho}} + \lambda e_{2,t}^{\frac{\rho-1}{\rho}}\right]^{\frac{\rho}{\rho-1}}$$

$$\sum_{t=0}^{\infty} e_{1,t} = R$$

Results, extended model



Results similar to benchmark case. (Preliminary calibration only, however.)

Concluding remarks

- We need a global macro framework.
- In it, limited natural resources appear increasingly needed:
  - limited short-run substitutability with other inputs in short run
  - shocks here offer potent source of fluctuations
  - yet in the medium run fairly stable share.
- The model we propose here could be a good beginning:
  - decent account of historical data on quantities and prices,
  - extension to "green technology" a way to think about future; appears to give similar results.