Natural resource economics

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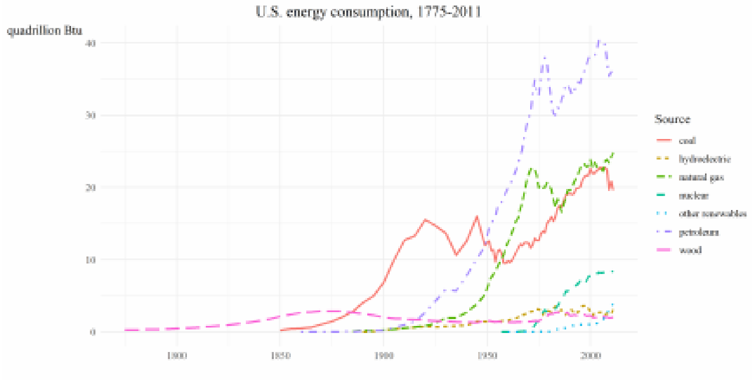
Natural resource economics

- There are a number of commodities - for instance fossil fuels - that are used as inputs in production function and whose available stock cannot be increased.
- One (old) questions is whether these resources are depleted too fast? Hotelling (JPE, 1931) writes:
- *Contemplation of the world's disappearing supplies of minerals, forests, and other exhaustible assets had led to demands for regulation of their exploitation. The feeling that these products are now too cheap for the good of future generations, that they are being selfishly exploited at too rapid a rate, and that in consequence of their excessive cheapness they are being produced and consumed wastefully has given rise to the conservation movement.*

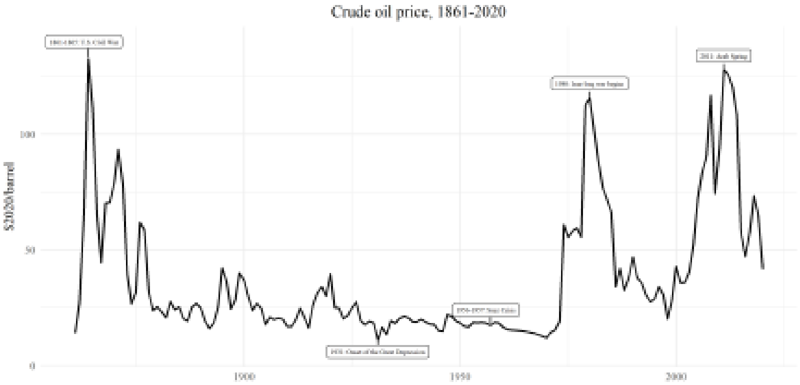
Other questions about natural resources

- At what rate should these resources optimally be depleted? Seminal paper by Dasgupta and Heal (REStud, 1974)—D&H from now on.
- What does depletion imply for the economy's growth rate?
- Must output eventually have to decline to zero?
- How should the prices of natural resources evolve?
- These problems received attention in the 1970s after the oil shocks.
- Can the models match the data?
- Let's start by looking at some data!

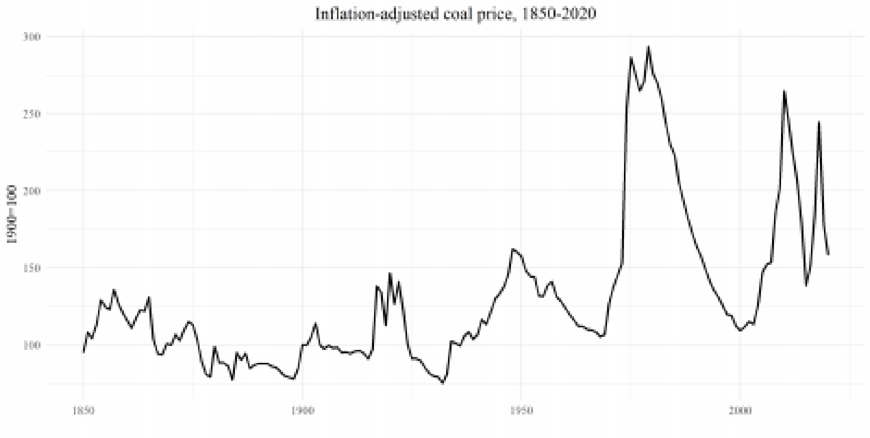
U.S. energy consumption



Oil prices



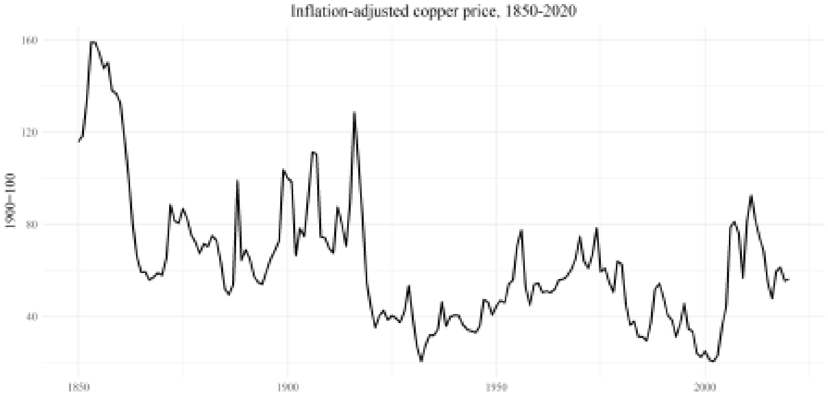
Coal prices


Inflation-adjusted coal price, 1850-2020
300
250
200
150
100
1900=100
1850
1900
1950
2000

Lead prices

Inflation-adjusted lead price, 1850-2020
1900=100
150
100
50
1850
1900
1950
2000

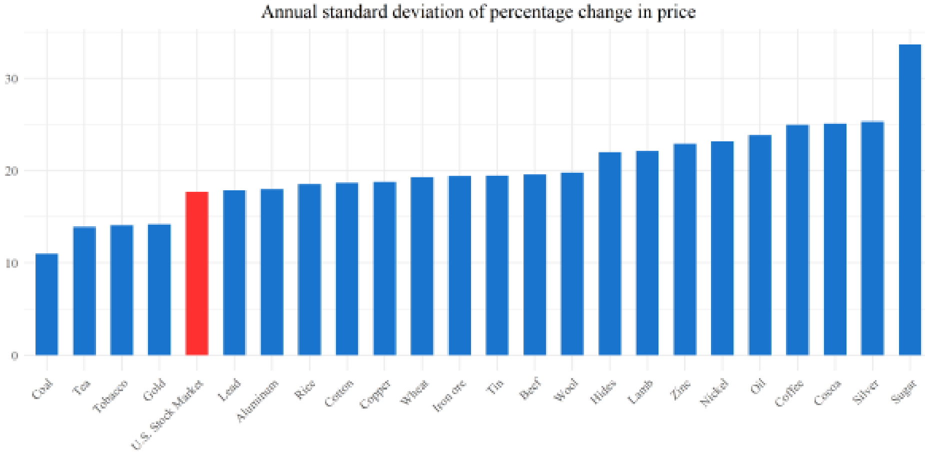
Copper prices



Zink prices

Inflation-adjusted zinc price, 1850-2020
1900=100
250
200
150
100
50
1850
1900
1950
2000

Price volatilities



Taking stock

- Commodity prices are very volatile.
- No clear long-run trends in prices. Some prices seems to be decreasing whereas others are increasing, but it is hard observe clear trends because of the large short-run fluctuations.
- Usage of the fossil fuels was increasing for a long time.

The simplest cake-eating problem

- Consider the classic problem of how to use a finite resource over an infinite number of periods.
- We abstract from externalities and taxes.
- Suppose that we have a given stock R of a resource, which cannot be increased.
- Question: how should we use it up over time?
- This is referred to as a cake-eating problem: R is the cake.

The model

- In the simplest case, the cake is eaten directly and there is nothing else to eat.
- Utility is logarithmic in consumption of the cake:

$$\max_{\{e_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log(e_t)$$

subject to

$$\sum_{t=0}^{\infty} e_t \leq R_0,$$

where β is the subjective discount factor.

Optimal cake eating

- Denote the multiplier on the resource constraint by μ. Then the foc w.r.t. e_t and e_{t+1} are respectively given by.

$$\begin{aligned} \beta^t \frac{1}{e_t} &= \mu \\ \beta^{t+1} \frac{1}{e_{t+1}} &= \mu. \end{aligned}$$

- Combining the these two equations, we get

$$\frac{e_{t+1}}{e_t} = \beta,$$

i.e. the depleation is monotonically decreasing.

- Using $e_{t+1} = \beta e_t$, $e_{t+2} = \beta^2 e_t$,..., we can write

$$\begin{aligned} e_t \sum_{t=0}^{\infty} \left(1 + \beta + \beta^2 + ...\right) &= R_t, \\ e_t &= \left(1 - \beta\right) R_t. \end{aligned}$$

The depletion rate

- Since $\beta < 1$, the consumption of the cake is *always* falling exponentially over time.
- Resource use could *never* increase!
- The depletion rate is independent of how large the cake is.
- We will see that this is surprisingly (but not completely) robust theoretical result.
- This is the social planning solution. Hence it is efficient.
- **But is is incapable of explaining the data!**
- And, what if we don't discount future welfare?

A model with capital and oil

- Let's add capital and look at the decentralized version of the model.
- Consider a representative agent with the following preferences

$$\sum_{t=0}^{\infty} \beta^t \log(c_t).$$

- The agent owns one unit of labor, owns the capital and the natural resource (oil). Factor prices w_t, r_t and p_t determined by marginal products.
- Sells all to the representative firm on competetive markets and decides consumption/saving. Capital depreciates fully so the constraints are

$$c_t + k_{t+1} = w_t l + r_t k_t + p_t e_t$$

and

$$\sum_{t=0}^{\infty} e_t \leq R_0$$

Market allocation

- The household problem is thus

$$\max_{\{k_{t+1},e_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log\left(w_t l + r_t k_t + p_t e_t - k_{t+1}\right) - \mu\left(\sum_{t=0}^{\infty} e_t - R_0\right).$$

- The first-order conditions for e_t and k_{t+1} are

$$\beta^t \frac{p_t}{c_t} - \mu = 0, \tag{1}$$

and

$$\beta^t \frac{1}{c_t} = \beta^{t+1} \frac{1}{c_{t+1}} r_{t+1} \Rightarrow \frac{c_{t+1}}{c_t} = \beta r_{t+1} \tag{2}$$

- Iterating (1) one period forward, we get

$$\begin{aligned} \frac{p_t}{c_t} &= \beta \frac{p_{t+1}}{c_{t+1}} \\ \frac{c_{t+1}}{c_t} &= \beta \frac{p_{t+1}}{p_t}. \end{aligned} \tag{3}$$

Hotelling 1931

- Now, combine the Euler equation $\frac{c_{t+1}}{c_t} = \beta r_{t+1}$ with the FOC w.r.t. e_t and e_{t+1}, i.e., $\frac{c_{t+1}}{c_t} = \beta \frac{p_{t+1}}{p_t}$. This gives famous *Hotelling formula* (after Hotelling, 1931)

$$\frac{p_{t+1}}{p_t} = r_{t+1},$$

  that states that the price of the natural resource should grow at a rate equal to the interest rate.
- Intuition: There are two ways of saving in this economy.
  1. The first is to save in the form of capital.
  2. The second is to save in the form of the resource – not using a unit of oil today and instead using it next period.
- In equilibrium, the return to these two types of savings must be equal. This is a very powerful arbitrage condition. It does not realy on the specific assumptions we used above.

Firms

- Let's use a Cobb-Douglas production function:

$$y_t = F(k_t, l, e_t) = A_t k_t^{\alpha} l^{1-\alpha-\nu} e_t^{\nu},$$

  where A_t is following some exogenous path of technological improvements.
- Note that e is an essential resource here since $F(k_t, l, 0) = 0$.
- Firms maximize profits

$$\pi = \max_{k_t, l, e_t} A_t k_t^{\alpha} l^{1-\alpha-\nu} e_t^{\nu} - w_t l - r_t k_t - p_t e_t$$

- The first-order conditions are that marginal products equal factor prices

$$\alpha \frac{y_t}{k_t} = r_t$$

$$(1-\alpha-\nu)\frac{y_t}{l} = w_t$$

  and

$$\nu \frac{y_t}{e_t} = p_t.$$

Solving the model

- Combining the Euler equation $\frac{c_{t+1}}{c(1-s_{t+1})_t} = \beta r_{t+1}$ and the firm's focs, we get
$$\frac{c_{t+1}}{c_t} = \beta\alpha \frac{y_{t+1}}{k_{t+1}}.$$
- Define the savings rate $s_t \equiv \frac{k_{t+1}}{y_t}$ so $c_t = (1 - s_t)\, y_t$ and $k_{t+1} = s_t y_t$.Then this is
$$\begin{aligned}\frac{(1-s_{t+1})\, y_{t+1}}{(1-s_t)\, y_t} &= \beta\alpha \frac{y_{t+1}}{s_t y_t} \\ .\frac{1-s_{t+1}}{1-s_t} &= \beta\alpha \frac{1}{s_t} \Rightarrow s_{t+1} = 1 - \beta\alpha \frac{(1-s_t)}{s_t}\end{aligned}$$
- This difference equation has a locally unstable steady state $s_t = \beta\alpha \forall t$. Any initial value larger than this leads to ever increasing savings rates converging to 1. Cannot be optimal (proof by checking transversality condition). Starting values below are not solutions since savings rate become negative. Thus, $s_t = \alpha\beta$ is optimal.

Path of energy use.

- Moving on, by again using the Euler equation and the Hotelling rule:

$$
\begin{aligned}
\frac{c_{t+1}}{c_t} &= \beta \frac{p_{t+1}}{p_t} \\
\frac{(1-s)y_{t+1}}{(1-s)y_t} &= \beta \frac{\nu y_{t+1}}{e_{t+1}} \frac{e_t}{\nu y_t} \\
1 &= \beta \frac{e_t}{e_{t+1}} \Rightarrow \frac{e_{t+1}}{e_t} = \beta .
\end{aligned}
$$

- This is the same solution as without capital. Again, resource use could never increase.

Price implications

- The model produces a balanced groth path where capital, output and consumption grows at a constant gross rate g. Let's determine this for an exogenous growth of A denoted g_A.
- From $A_t k_t^{\alpha} l^{1-\alpha-\nu} e_t^{\nu}$ and noting that the growth rates of k equals g and of that of e equals β, we get

$$g = g_A g^{\alpha} \beta^{\nu} \Rightarrow g = g_A^{\frac{1}{1-\alpha}} \beta^{\frac{\nu}{1-\alpha}}.$$

  - Note that this is a an endogenous growth rate.The economy is shrinking over time unless $g_A \geq \beta^{-\nu}$.
- The condition is stricter the lower is β and the higher is ν. Interpretation!

A more general formula for the Hotelling rule

- Recall that the Hotelling equation is an arbitrage condition. Then, it is really the return of saving oil that should equal the return on saving in the form of capital. With costs of extraction, the return on saving oil is

$$\frac{p_{t+1} - mc_{t+1}}{p_t - mc_t} = 1 + r_{t+1},$$

  where mc_{t+1} is the marginal cost of extraction.

- $$\frac{p_{e,t+1}}{p_{e,t}} = 1 + r_{t+1} + \frac{1}{p_{e,t}} \left(mc_{t+1} - (1 + r_{t+1})\, mc_t \right).$$

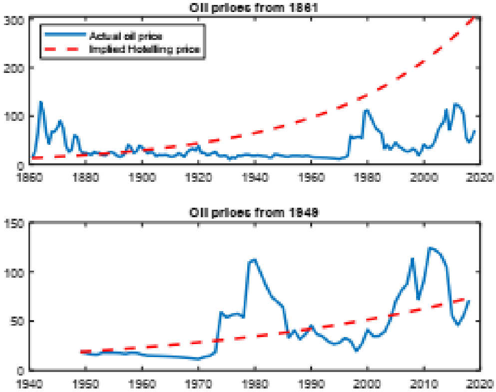
- If the marginal cost is raising slower than the interest rate, for example if they are constant, then prices will also grow at a slower rate.
- With data on marginal costs, this could be tested directly.

Can market power save Hotelling rule?

- Disregard again extraction costs but assume market power. Then, the Hotelling becomes
$$\frac{mr_{t+1}}{mr_t} = r_{t+1},$$
where mr_t is the marginal revenue.
- Assume not unreasonably a constant elastic demand, in which case marginal revenue is proportional to the price. Then, we get
$$\begin{aligned} \frac{\mu p_{t+1}}{\mu p_t} &= r_{t+1} \\ \frac{p_{t+1}}{p_t} &= r_{t+1} \end{aligned}$$
- So exactly the same allocation as without market power!.

Hotelling and data

- Is Hotelling a reasonable prediction for oil?



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- Maybe from the post-war period – but a stretch.
- For many (most?) resources however, the Hotelling rule seems to be strongly rejected.

The Hotelling rule in general

- Krautkraemer (JEL, 1998) writes:

For the most part, the implications of this basic Hotelling model have not been consistent with empirical studies of nonrenewable resource prices and in situ values. There has not been a persistent increase in nonrenewable resource prices over the last 125 years, but rather fluctuations around time trends whose direction can depend upon the time period selected as a vantage point.

Potential reasons for the breakdown

- The possibility of a, so called, backstop technology may make the resource abundant and without scarcity rent.
- Incorrect perceptions of future oil prices and/or about the existing stock of the resource.
- Lack of property rights.
- Myopia.
- Risk and imperfect market for insurance and selling oil in ground.

How to model?

- Modeling fossil fuel as a limited stock where price is the scarcity rent implying that prices follows the Hotelling rule does not work.
- This casts doubt on Sinn's Green Paradox – that expectations of future restrictive climate policies are self-defeating by increasing extraction rates.
- Probably better to model the market as one with infinite (long-run) supply so price is equal to marginal extraction cost without rents. Technical change and increased difficulty in recovering the fuel (have to dig deeper) has a horse race determining whether prices increase or fall over time.

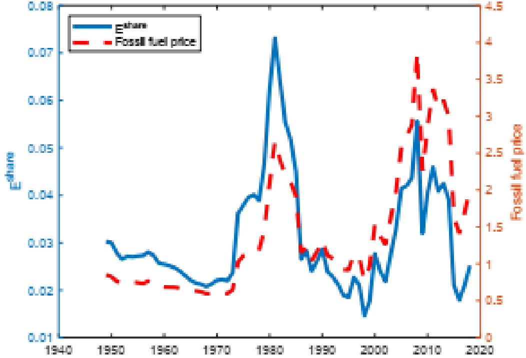
Short run inflexibility and income shares

- So far, we have used a production function that was of the Cobb-Douglas type: $y_t = k_t^{\alpha} l_t^{1-\alpha-\nu} e_t^{\nu}$.
- The Cobb-Douglas has a few particular properties. First, the exponent denotes the income share of the variable. Hence,

$$\frac{p_t e_t}{y_t} = \nu$$

  determines energy's share of income. In addition, it is constant!
- Reasonable? Let's look at some more data!

Energy's share of income



- In the short to medium run, the share follows the price and is far from constant.The C-D function may not be appropriate,
- No obvious long-run trend.
- Smoking gun: energy is not substitutatble with other inputs in the

An alternative production function

The model above had

$$U = \max_{\{c_t, k_{t+1}, e_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t \log(c_t),$$

$$\text{s.t. } c_t + k_{t+1} = y_t \text{ and } \sum_{t=0}^{\infty} e_t \leq R_0,$$

where y was Cobb-Douglas. Consider now the same model with one modification: a CES production function:

$$y_t = \left[\left(A_t k_t^{\alpha} l_t^{1-\alpha}\right)^{\frac{\varepsilon-1}{\varepsilon}} + \left(A_{e,t} e_t\right)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}},$$

where ε determines the elasticity of substitution between the inputs.

- With $\varepsilon = 0$, we get Leontief (perfect complements), with $\varepsilon = 1$, Cobb-Douglas, and $\varepsilon = \infty$, perfect substitutes. What is reasonable?
- A_t is a productivity component that improves the capital/labor productivity, whereas $A_{e,t}$ affects the energy efficiency.

Input efficiencies

- With profit maximization and competitive input markets, these technolog trends can be expressed as

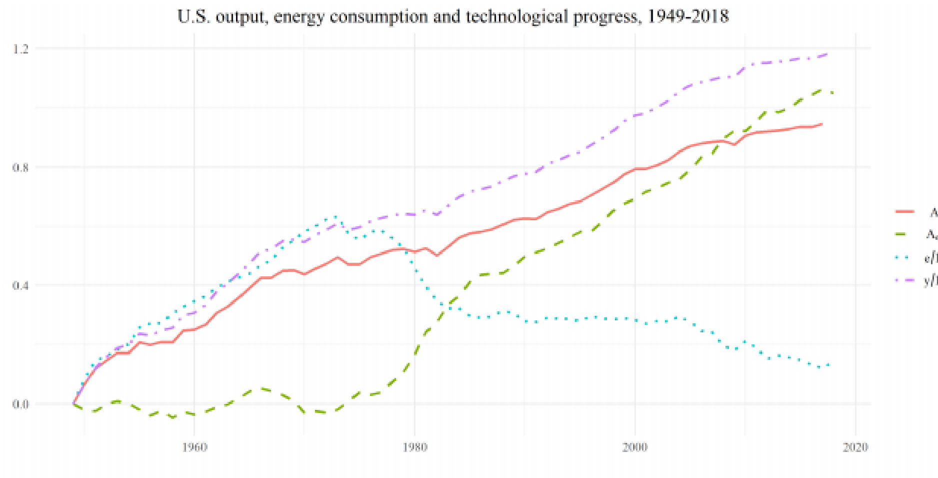
$$A_t = \frac{y_t}{k_t^{\alpha} l_t^{1-\alpha}} \left(\frac{l_t^{share}}{1-\alpha} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

  and

$$A_{et} = \frac{y_t}{e_t} \left(e_t^{share} \right)^{\frac{\varepsilon}{\varepsilon-1}} ,$$

  where $l_t^{share} \equiv w_t l_t / y_t$ and $e_t^{share} = p_t e_t / y_t$.

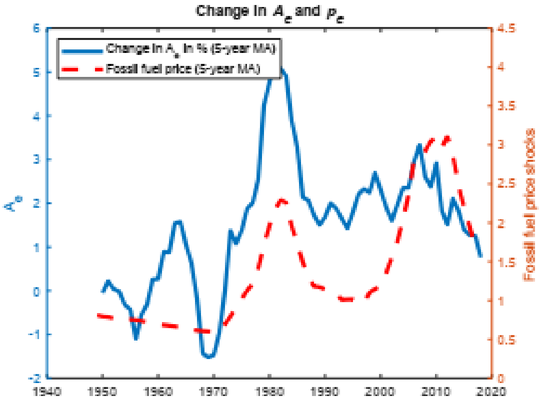
- Hassler, Krusell, and Olovsson (JPE, 2021—HKO from now on) use data from the National Accounts and the Energy Information Administration on y_t, k_t, l_t, e_t, and p_t to compute A and A_e.
- How have A and A_e evolved over time?


U.S. output, energy consumption and technological progress, 1949-2018
1.2
0.8
0.4
0.0
1960
1980
2000
2020

The figure in words

- Energy use per person increases and follows output growth closely up to the early 1970s.
  - During this time, there is little improvement in the energy efficiency (A_e is roughly constant), whereas A is growing fast.
- Around the time of the first oil shock (1973), energy use starts falling and the growth rate of the energy efficiency increases substantially.
- Energy use *in efficiency units*, $A_e e$, follows GDP closely.
  - In the short run, increases in GDP will be accompanied by increases in e, but over the longer run, the increase comes from higher energy efficiency and e can fall.
- A trade off: when A_e is growing faster, A is growing slower and vice versa.

Changes in energy efficiency and the fossil-fuel price



- When the price goes up, energy efficiency improves faster and vice versa.
- Hence, energy efficiency seems to be endogenous. Need to model!